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Terrestrial and Inland Water Systems

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Executive Summary

The planet's biota and ecosystem processes were strongly affected by past climate changes at rates of climate change lower than those projected during the 21st century under high warming scenarios (e.g., Representative Concentration Pathway 8.5 (RCP8.5)) (*high confidence*). Most ecosystems are vulnerable to climate change even at rates of climate change projected under low- to medium-range warming scenarios (e.g., RCP2.6 to RCP6.0). The paleoecological record shows that global climate changes comparable in magnitudes to those projected for the 21st century under all scenarios resulted in large-scale biome shifts and changes in community composition; and that for rates projected under RCP6 and 8.5 were associated with species extinctions in some groups (*high confidence*). {4.2.3}

Climate change is projected to be a powerful stressor on terrestrial and freshwater ecosystems in the second half of the 21st century, especially under high-warming scenarios such as RCP6.0 and RCP8.5 (*high confidence*). Direct human impacts such as land use and land use change, pollution, and water resource development will continue to dominate the threats to most freshwater (*high confidence*) and terrestrial (*medium confidence*) ecosystems globally over the next 3 decades. Changing climate exacerbates other impacts on biodiversity (*high confidence*). Ecosystem changes resulting from climate change may not be fully apparent for several decades, owing to long response times in ecological systems (*medium confidence*). Model-based projections imply that under low to moderate warming scenarios (e.g., RCP2.6 to RCP6.0), direct land cover change will continue to dominate over (and conceal) climate-induced change as a driver of ecosystem change at the global scale; for higher climate change scenarios, some model projections imply climate-driven ecosystem changes sufficiently extensive to equal or exceed direct human impacts at the global scale (*medium confidence*). In high-altitude and high-latitude freshwater and terrestrial ecosystems, climate changes exceeding those projected under RCP2.6 will lead to major changes in species distributions and ecosystem function, especially in the second half of the 21st century (*high confidence*). {4.2.4, 4.3.2.5, 4.3.3, 4.3.3.1, 4.3.3.3, 4.4.1.1}

When terrestrial ecosystems are substantially altered (in terms of plant cover, biomass, phenology, or plant group dominance), either through the effects of climate change or through other mechanisms such as conversion to agriculture or human settlement, the local, regional, and global climates are also affected (*high confidence*). The feedbacks between terrestrial ecosystems and climate include, among other mechanisms, changes in surface albedo, evapotranspiration, and greenhouse gas (GHG) emissions and uptake. The physical effects on the climate can be opposite in direction to the GHG effects, and can materially alter the net outcome of the ecosystem change on the global climate (*high confidence*). The regions where the climate is affected may extend beyond the location of the ecosystem that has changed. {4.2.4.1, 4.3.3.4}

Rising water temperatures, due to global warming, will lead to shifts in freshwater species distributions and worsen water quality problems, especially in those systems experiencing high anthropogenic loading of nutrients (*high confidence*). Climate change-induced changes in precipitation will substantially alter ecologically important attributes of flow regimes in many rivers and wetlands and exacerbate impacts from human water use in developed river basins (*medium confidence*). {4.3.3.3, Box CC-RF}

Many plant and animal species have moved their ranges, altered their abundance, and shifted their seasonal activities in response to observed climate change over recent decades (*high confidence*). They are doing so now in many regions and will continue to do so in response to projected future climate change (*high confidence*). The broad patterns of species and biome shifts toward the poles and higher in altitude in response to a warming climate are well established for periods thousands of years in the past (*very high confidence*). These general patterns of range shifts have also been observed over the last few decades in some well-studied species groups such as insects and birds and can be attributed to observed climatic changes (*high confidence*). Interactions between changing temperature, precipitation, and land use can sometimes result in range shifts that are downhill or away from the poles. Certainty regarding past species movements in response to changing climate, coupled with projections from a variety of models and studies, provides *high confidence* that such species movements will be the norm with continued warming. Under all RCP climate change scenarios for the second half of the 21st century, with *high confidence*: (1) community composition will change as a result of decreases in the abundances of some species and increases in others; and (2) the seasonal activity of many species will change differentially, disrupting life cycles and interactions between species. Composition and seasonal change will both alter ecosystem function. {4.2.1, 4.2.3, 4.3.2, 4.3.2.1, 4.3.2.5, 4.3.3, 4.4.1.1}

Many species will be unable to move fast enough during the 21st century to track suitable climates under mid- and high-range rates of climate change (i.e., RCP4.5, RCP6.0, and RCP8.5 scenarios) (*medium confidence*). The climate velocity (the rate of movement of the climate across the landscape) will exceed the maximum velocity at which many groups of organisms, in many situations, can disperse or migrate, except after mid-century in the RCP2.6 scenario. Populations of species that cannot keep up with their climate niche will find themselves in unfavorable climates, unable to reach areas of potentially suitable climate. Species occupying extensive flat landscapes are particularly vulnerable because they must disperse over longer distances than species in mountainous regions to keep pace with shifting climates. Species with low dispersal capacity will also be especially vulnerable: examples include many plants (especially trees), many amphibians, and some small mammals. For example, the maximum observed and modeled dispersal and establishment rates for mid- and late-successional tree species are insufficient to track climate change except in mountainous areas, even at moderate projected rates of climate change. Barriers to dispersal, such as habitat fragmentation, prior occupation of habitat by competing species, and human-made impediments such as dams on rivers and urbanized areas on land, reduce the ability of species to migrate to more suitable climates (*high confidence*). Intentional and accidental anthropogenic transport can speed dispersal. {4.3.2.5, 4.3.3.3}

Large magnitudes of climate change will reduce the populations, vigor, and viability of species with spatially restricted populations, such as those confined to small and isolated habitats, mountaintops, or mountain streams, even if the species has the biological capacity to move fast enough to track suitable climates (*high confidence*). The adverse effects on restricted populations are modest for low magnitudes of climate change (e.g., RCP2.6) but very severe for the highest magnitudes of projected climate change (e.g., RCP8.5). {4.3.2.5, 4.3.3.4, 4.3.4.1}

The capacity of many species to respond to climate change will be constrained by non-climate factors (*high confidence*), including but not limited to the simultaneous presence of inhospitable land uses, habitat fragmentation and loss, competition with alien species, exposure to new pests and pathogens, nitrogen loading, and tropospheric ozone. {4.2.4.6, 4.3.3.5, Figure 4-4}

The establishment, growth, spread, and survival of populations of invasive alien species have increased (*high confidence*), but the ability to attribute alien species invasion to climate change is low in most cases. Some invasive alien species have traits that favor their survival and reproduction under changing climates. Future movement of species into areas where they were not present historically will continue to be driven mainly by increased dispersal opportunities associated with human activities and by increased disturbances from natural and anthropogenic events, in some cases facilitated and promoted by climate change. {4.2.4.6, Figure 4-4}

A large fraction of terrestrial and freshwater species face increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other pressures, such as habitat modification, overexploitation, pollution, and invasive species (*high confidence*). The extinction risk is increased under all RCP scenarios, and the risk increases with both the magnitude and rate of climate change. While there is *medium confidence* that recent warming contributed to the extinction of some species of Central American amphibians, there is generally *very low confidence* that observed species extinctions can be attributed to recent climate change. Models project that the risk of species extinctions will increase in the future owing to climate change, but there is *low agreement* concerning the fraction of species at increased risk, the regional and taxonomic focus for such extinctions and the time frame over which extinctions could occur. Modeling studies and syntheses since the AR4 broadly confirm that a large proportion of species are projected to be at increased risk of extinction at all but the lowest levels of climate warming (RCP2.6). Some aspects leading to uncertainty in the quantitative projections of extinction risks were not taken into account in previous models; as more realistic details are included, it has been shown that the extinction risks may be either under- or overestimated when based on simpler models. {4.3.2.5}

Terrestrial and freshwater ecosystems have sequestered about a quarter of the carbon dioxide (CO₂) emitted to the atmosphere by human activities in the past 3 decades (*high confidence*). The net fluxes out of the atmosphere and into plant biomass and soils show large year-to-year variability; as a result there is *low confidence* in the ability to determine whether the net rate at which carbon has been taken up by terrestrial ecosystems at the global scale has changed between the decades 1991–2000 and 2001–2010. There is *high confidence* that the factors causing the current increase in land carbon include the positive effects of rising CO₂ on plant productivity, a warming climate, nitrogen deposition, and recovery from past disturbances, but *low confidence* regarding the relative contribution by each of these and other factors. {4.2.4.1, 4.2.4.2, 4.2.4.4, 4.3.2.2, 4.3.2.3, WGI AR5 6.3.1, 6.3.2.6}

The natural carbon sink provided by terrestrial ecosystems is partially offset at the decadal time scale by carbon released through the conversion of natural ecosystems (principally forests) to farm and grazing land and through ecosystem degradation (*high confidence*). Carbon stored in the terrestrial biosphere is vulnerable to loss back to the atmosphere as a result of the direct and indirect effects of climate change, deforestation, and degradation (*high confidence*). The net transfer of CO₂ from the atmosphere to the land is projected to weaken during the 21st century (*medium confidence*). The direct effects of climate change on stored terrestrial carbon include high temperatures, drought, and windstorms; indirect effects include increased risk of fires and pest and disease outbreaks. Experiments and modeling studies provide *medium confidence* that increases in CO₂ up to about 600 ppm will continue to enhance photosynthesis and plant water use efficiency, but at a diminishing rate; and *high confidence* that low availability of nutrients, particularly nitrogen, will limit the response of many natural ecosystems to rising CO₂. There is *medium confidence* that other factors associated with global change, including high temperatures, rising ozone concentrations, and in some places drought, decrease plant productivity by amounts comparable in magnitude to the enhancement by rising CO₂. There are few field-scale experiments on ecosystems at the highest CO₂ concentrations projected by RCP8.5 for late in the century, and none of these include the effects of other potential confounding factors. {4.2.4, 4.2.4.1, 4.2.4.2, 4.2.4.3, 4.2.4.4, 4.3.2.2, 4.3.3.1, Box 4-3, Box CC-VW, WGI AR5 6.4.3.3}

Increases in the frequency or intensity of ecosystem disturbances such as droughts, wind storms, fires, and pest outbreaks have been detected in many parts of the world and in some cases are attributed to climate change (*medium confidence*). Changes in the ecosystem disturbance regime beyond the range of natural variability will alter the structure, composition, and functioning of ecosystems (*high confidence*). Ecological theory and experimentation predict that ecological change resulting from altered disturbance regimes will be manifested as relatively abrupt and spatially patchy transitions in ecosystem structure, composition, and function, rather than gradual and spatially uniform shifts in location or abundance of species (*medium confidence*). {4.2.4.6, 4.3.3, 4.3.2.5, Box 4-3, Box 4-4, Figure 4-10}

Increased tree death has been observed in many places worldwide, and in some regions has been attributed to climate change (*high confidence*). In some places it is sufficiently intense and widespread as to result in forest dieback (*low confidence*). Forest dieback is a major environmental risk, with potentially large impacts on climate, biodiversity, wood production, water quality, amenity, and economic activity. In detailed regional studies in western and boreal North America, the tree mortality observed over the past few decades has been attributed to the effects of high temperatures and drought, or to changes in the distribution and abundance of insect pests and pathogens related, in part, to warming (*high confidence*). Tree mortality and associated forest dieback will become apparent in many regions sooner than previously anticipated (*medium confidence*). Earlier projections of increased tree growth and enhanced forest carbon sequestration due to increased growing season duration, rising CO₂ concentration, and atmospheric nitrogen deposition must be balanced by observations and projections of increasing tree mortality and forest loss due to fires and pest attacks. The consequences for the provision of timber and other wood products are projected to be highly variable between regions and products, depending on the balance of the positive versus negative effects of global change. {4.3.2, 4.3.3.1, 4.3.3.4, 4.3.3.5, 4.3.4, 4.3.4.2, Box 4-2, Box 4-3}

There is a high risk that the large magnitudes and high rates of climate change associated with low-mitigation climate scenarios (RCP4.5 and higher) will result within this century in abrupt and irreversible regional-scale change in the composition, structure, and function of terrestrial and freshwater ecosystems, for example in the Amazon (*low confidence*) and Arctic (*medium confidence*), leading to substantial additional climate change. There are plausible mechanisms, supported by experimental evidence, observations, and model results, for the existence of ecosystem tipping points in both boreal-tundra Arctic systems and the rainforests of the Amazon basin. Continued climate change will transform the species composition, land cover, drainage, and permafrost extent of the boreal-tundra system, leading to decreased albedo and the release of GHGs (*medium confidence*). Adaptation measures will be unable to prevent substantial change in the boreal-Arctic system (*high confidence*). Climate change alone is not projected to lead to abrupt widespread loss of forest cover in the Amazon during this century a (*medium confidence*), but a projected increase in severe drought episodes, together with land use change and forest fire, would cause much of the Amazon forest to transform to less dense, drought- and fire-adapted ecosystems, and in doing so put a large stock of biodiversity at elevated risk, while decreasing net carbon uptake from the atmosphere (*low confidence*). Large reductions in deforestation, as well as wider application of effective wildfire management, lower the risk of abrupt change in the Amazon, as well as the impacts of that change (*medium confidence*). {4.2.4.1, 4.3.3.1.1, 4.3.3.1.3, 4.3.3.4, Figure 4-8, Box 4-3, Box 4-4}

Management actions can reduce, but not eliminate, the risk of impacts to terrestrial and freshwater ecosystems due to climate change, as well as increase the inherent capacity of ecosystems and their species to adapt to a changing climate (*high confidence*).

The capacity for natural adaptation by ecosystems and their constituent organisms is substantial, but for many ecosystems and species it will be insufficient to cope with projected rates and magnitudes of climate change in the 21st century without substantial loss of species and ecosystem services, under medium-range warming (e.g., RCP6.0) or high-range warming scenarios (e.g., RCP8.5) (*medium confidence*). The capacity for ecosystems to adapt to climate change can be increased by reducing the other stresses operating on them; reducing the rate and magnitude of climate change; reducing habitat fragmentation and increasing connectivity; maintaining a large pool of genetic diversity and functional evolutionary processes; assisted translocation of slow moving organisms or those whose migration is impeded, along with the species on which they depend; and manipulation of disturbance regimes to keep them within the ranges necessary for species persistence and sustained ecosystem functioning. {4.4, 4.4.1, 4.4.2}

Adaptation responses to climate change in the urban and agricultural sectors can have unintended negative outcomes for terrestrial and freshwater ecosystems (*medium confidence*). For example, adaptation responses to counter increased variability of water supply, such as building more and larger impoundments and increased water extraction, will in many cases worsen the direct effects of climate change in freshwater ecosystems. {4.3.3.3, 4.3.4.6}

Widespread transformation of terrestrial ecosystems in order to mitigate climate change, such as carbon sequestration through planting fast-growing tree species into ecosystems where they did not previously occur, or the conversion of previously uncultivated or non-degraded land to bioenergy plantations, will lead to negative impacts on ecosystems and biodiversity (*high confidence*). For example, the land use scenario accompanying the mitigation scenario RCP2.6 features a large expansion of biofuel production, displacing natural forest cover. {4.2.4.1, 4.4.4}

4.1. Past Assessments

The topics assessed in this chapter were last assessed by the IPCC in 2007, principally in WGII AR4 Chapters 3 (Kundzewicz et al., 2007) and 4 (Fischlin et al., 2007), but also in WGII AR4 Sections 1.3.4 and 1.3.5 (Rosenzweig et al., 2007). The WGII AR4 SPM stated “Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases,” though they noted that documentation of observed changes in tropical regions and the Southern Hemisphere was sparse (Rosenzweig et al., 2007). Fischlin et al. (2007) found that 20 to 30% of the plant and animal species that had been assessed to that time were considered to be at increased risk of extinction if the global average temperature increase exceeds 2°C to 3°C above the preindustrial level with *medium confidence*, and that substantial changes in structure and functioning of terrestrial, marine, and other aquatic ecosystems are *very likely* under that degree of warming and associated atmospheric CO₂ concentration. No time scale was associated with these findings. The carbon stocks in terrestrial ecosystems were considered to be at high risk from climate change and land use change. The report warned that the capacity of ecosystems to adapt naturally to the combined effect of climate change and other stressors is likely to be exceeded if greenhouse gas (GHG) emission continued at or above the then-current rate.

4.2. A Dynamic and Inclusive View of Ecosystems

There are three aspects of the contemporary scientific view of ecosystems that are important to know for policy purposes. First, ecosystems usually have imprecise and variable boundaries. They span a wide range of spatial scales, nested within one another, from the whole biosphere, down through its major ecosystem types (biomes), to local and possibly short-lived associations of organisms. Second, the human influence on ecosystems is globally pervasive. Humans are regarded as an integral, rather than separate, part of social-ecological systems (Gunderson and Holling, 2001; Berkes et al., 2003). Ecosystems are connected across boundaries through the movement of energy, materials, and organisms, and subsidies between terrestrial and freshwater systems are known to be particularly important (Polis et al., 1997; Loreau et al., 2003). As a consequence, human activities in terrestrial systems can significantly impact freshwater ecosystems and their biota (Allan, 2004). The dynamics of socio-ecological systems 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). Third, ecologists do not view ecosystems as necessarily inherently static and at equilibrium in the absence of a human disturbance (Hastings, 2004). Ecosystems vary over time and space in the relative magnitude of their components and fluxes, even under a constant environment, owing to internal dynamics (Scheffer, 2009). Furthermore, attempts to restrict this intrinsic variation—or that resulting from externally generated disturbances—are frequently futile, and may damage the capacity of the ecosystem to adapt to a changing environment (Folke et al., 2004). This contrasts with the popular view that ecosystems exhibit a “balance of Nature” and benefit from being completely protected from disturbance.

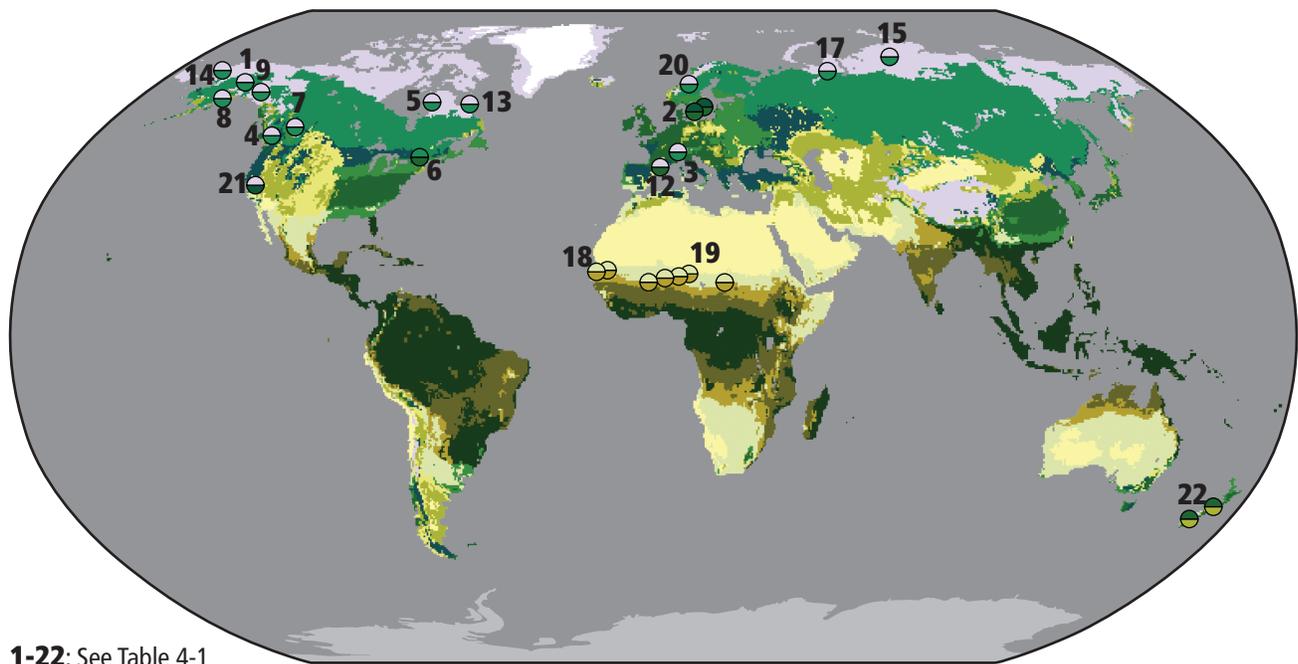
4.2.1. Ecosystems, Adaptation, Thresholds, and Tipping Points

The term “adaptation” has different meanings in climate policy, ecology, and evolutionary biology. In climate policy (see Glossary) it implies human actions intended to reduce negative outcomes. In ecology, ecosystems are said to be adaptive because their composition or function can change in response to a changing environment, without necessarily involving deliberate human actions (see Section 4.4.1). In evolutionary biology, adaptation means a change in the genetic properties of a population of individuals as a result of natural selection (Section 4.4.1.2), a possibility seen since the Fourth Assessment Report as increasingly relevant to climate change.

The notion of thresholds has become a prominent ecological and political concern (Knapp, A.K. et al., 2008; Lenton et al., 2008; Leadley et al., 2010). To avoid policy confusion, three types of threshold need to be distinguished. The first reflects a human preference that the ecosystem stays within certain bounds, such as above a certain forest cover. These can be, by definition, negotiated. The second type reflects fundamental biological or physical properties, for instance the temperature at which frozen soils thaw (see Box 4-4) or the physiological tolerance limits of species. The third type is caused by system dynamics: the point at which the net effect of all the positive and negative feedback loops regulating the system is sufficiently large and positive that a small transgression becomes sufficiently amplified to lead to a change in ecosystem state called a regime shift (Lenton et al., 2008). The new state exhibits 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” (defined in the Glossary as a level of change in system properties beyond which a system reorganizes, often abruptly, and persists in its new state even if the drivers of the change are abated) and is important in the context of climate change because its onset may be abrupt, hard to predict precisely, and effectively irreversible (Scheffer et al., 2009; Leadley et al., 2010; Barnosky et al., 2012; Brook et al., 2013; Hughes et al., 2013). Many examples of tipping points have now been identified (Scheffer, 2009). Regional-scale ecosystem tipping points have not occurred in the recent past, but there is good evidence for tipping points in the distant past (Section 4.2.3) and there is concern that they could occur in the near future (see Boxes 4-3 and 4-4).

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 the threshold is crossed (Biggs et al., 2009). The dynamics of ecosystems are complex and our present level of knowledge is inadequate to predict all ecosystem outcomes with confidence, even if the future climate were precisely known.

Field observations over the past century in numerous locations in boreal, temperate, and tropical ecosystems have detected biome shifts, the replacement at a location of one suite of species by another (*high confidence*). The effect is usually of biomes moving upward in elevation and to higher latitudes (Gonzalez et al., 2010; see Figure 4-1). These shifts



1-22: See Table 4-1

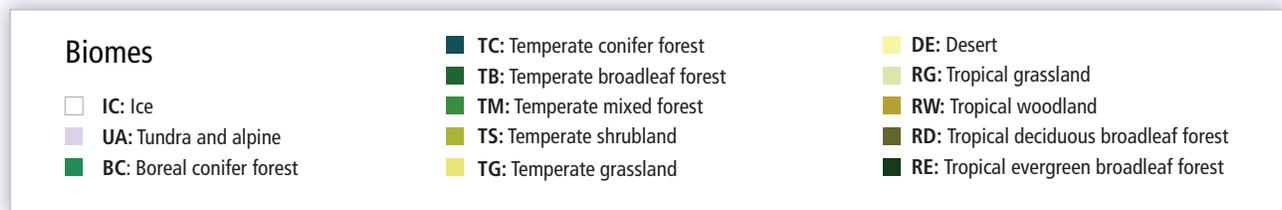


Figure 4-1 | Locations of observed biome shifts during the 20th century, listed in Table 4-1, derived from Gonzalez et al. (2010). The color of each semicircle indicates the retracting biome (top for North America, Europe, Asia; bottom for Africa and New Zealand) and the expanding biome (bottom for North America, Europe, Asia; top for Africa and New Zealand), according to published field observations. Biomes, from poles to equator: ice (IC), tundra and alpine (UA), boreal conifer forest (BC), temperate conifer forest (TC), temperate broadleaf forest (TB), temperate mixed forest (TM), temperate shrubland (TS), temperate grassland (TG), desert (DE), tropical grassland (RG), tropical woodland (RW), tropical deciduous broadleaf forest (RD), tropical evergreen broadleaf forest (RE). The background is the potential biome according to the MC1 dynamic global vegetation model under the 1961–1990 climate. No shift was observed on locations 10, 11, 16, and 23 (see Table 4-1).

have often been attributed to anthropogenic climate change, as biome distribution is known to broadly reflect climate zones, and the shifts have been observed in areas without major human disturbance (*medium confidence*; see Table 4-1). Projections of future vegetation distribution under climate change indicate that many biomes could shift substantially, including in areas where ecosystems are largely undisturbed by direct human land use (Figure 4-2). The extent of the shift increases with increasing global mean warming, without a sudden threshold (Scholze et al., 2006; Pereira et al., 2010; Rehfeldt et al., 2012).

4.2.2. Methods and Models Used

Analysis of the current and past impacts of climate change on terrestrial and freshwater ecosystems and their projection into the future relies on three general approaches: inference from analogous situations in the past or elsewhere in the present; manipulative experimentation, deliberately altering one of a few factors at a time; and models with a mechanistic or statistical basis. Studies of the relatively distant past are discussed in depth in Section 4.2.3. Inferences from present spatial

patterns in relation to climate is at the core of climate envelope niche modeling, a well-established but limited statistical technique for making projections of the future distribution under equilibrium conditions (Elith and Leathwick, 2009). Representing the rate of change during the non-equilibrium conditions that will prevail over the next century requires a more mechanistic approach, of which there are some examples (e.g., Keith et al., 2008; Kearney and Porter, 2009). Changes in ecosystem function are usually determined by experimentation (see examples in Section 4.3.3) and are modeled using mechanistic models, in many cases with relatively high uncertainty (Seppelt et al., 2011).

4.2.3. Paleocological Evidence

Paleoclimatic observations and modeling 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; see WGI AR5 Chapter 5). Paleocological records demonstrate with *high confidence* that the planet’s biota (both terrestrial and aquatic),

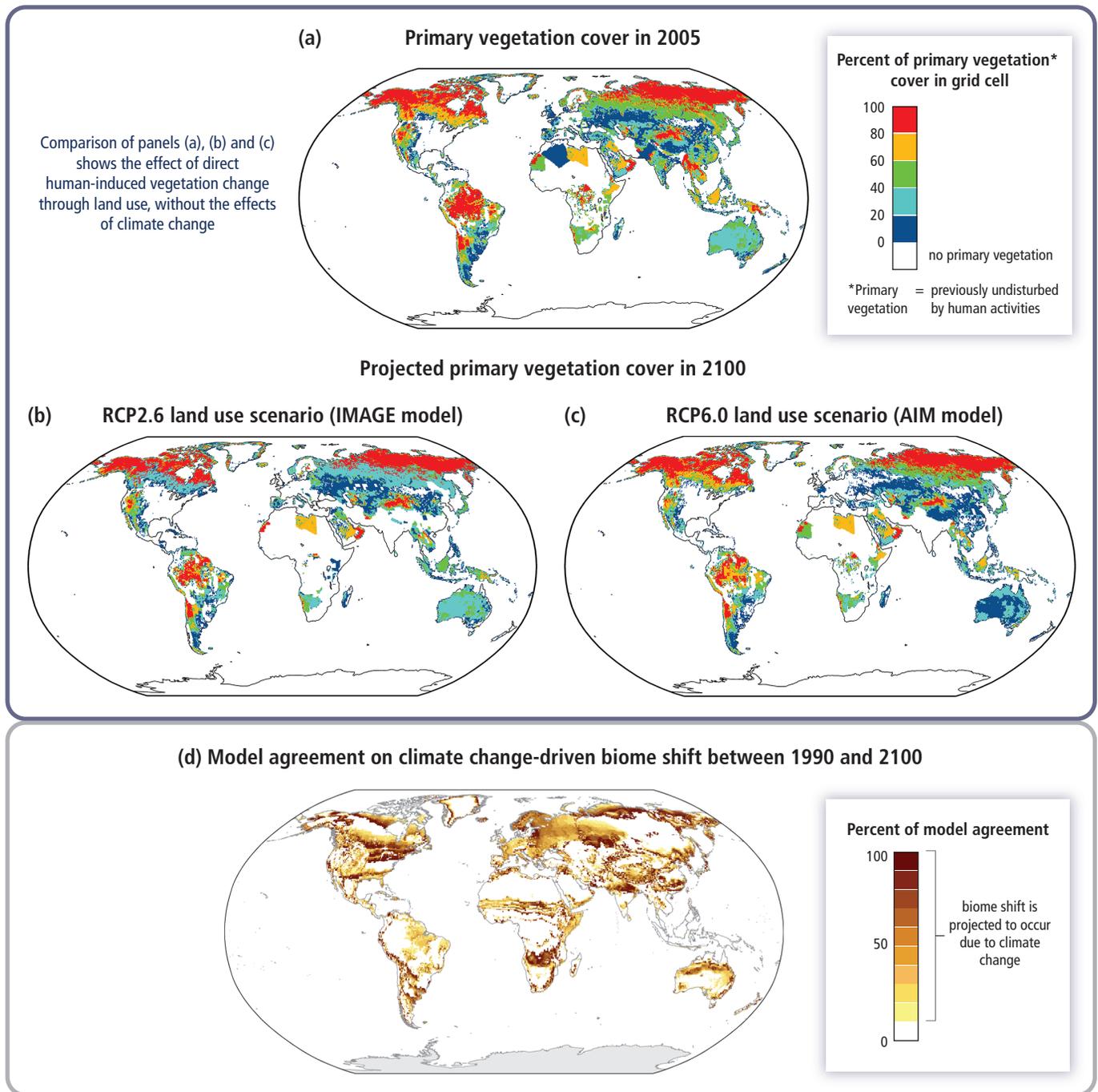
Table 4-1 | Biome shifts of the 20th century from published field research that examined trends over periods >30 years for biomes in areas where climate (rather than land use change or other factors) predominantly influenced vegetation, derived from a systematic analysis of published studies (Gonzalez et al., 2010). Pre-AR4 publications are included to provide a comprehensive review. Shift type: elevational (E), latitudinal (L), examined but not detected (N). The biome abbreviations match those in Figure 4-1. 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 ⁻¹)	Precip. change (% century ⁻¹)
1. Alaska Range, Alaska, USA	Lloyd and Fastie (2003)	18	1800–2000	L	UA	BC	1.1*	3
2. Baltic Coast, Sweden	Walther et al. (2005)	7	1944–2003	L	TC	TB	0.6*	8
3. Becca di Viou, Italy	Leonelli et al. (2011)	1	1700–2008	E	UA	BC	0.9*	–6
4. Garibaldi, British Columbia, Canada	Brink (1959)	1	1860–1959	E	UA	BC	0.7*	16*
5. Goulet Sector, Québec, Canada	Payette and Filion (1985)	2	1880–1980	E	UA	BC	1.4*	19*
6. Green Mountains, Vermont, USA	Beckage et al. (2008)	33	1962–2005	E	BC	TB	1.6*	6
7. Jasper, Alberta, Canada	Luckman and Kavanagh (2000)	1	1700–1994	E	UA	BC	0.6	21*
8. Kenai Mountains, Alaska, USA	Dial et al. (2007)	3	1951–1996	E	UA	BC	0.7	6
9. Kluane Range, Yukon, Canada	Danby and Hik (2007)	2	1800–2000	E	UA	BC	0.7	5
10. Low Peninsula, Québec, Canada	Payette and Filion (1985)	1	1750–1980	N	—	—	1.4*	19*
11. Mackenzie Mountains, Northwest Territories, Canada	Szeicz and Macdonald (1995)	13	1700–1990	N	—	—	1.4*	3
12. Montseny Mountains, Catalonia, Spain	Peñuelas and Boada (2003)	50	1945–2001	E	UA	TB	1.2*	–3
13. Napaktok Bay, Labrador, Canada	Payette (2007)	2	1750–2000	L	UA	BC	1.1*	5
14. Noatak, Alaska, USA	Suarez et al. (1999)	18	1700–1990	L	UA	BC	0.6	19*
15. Putorana Mountains, Russian Federation	Kirdyanov et al. (2012)	10	1500–2000	E	UA	BC	0.3	10
16. Rahu Saddle, New Zealand	Cullen et al. (2001)	7	1700–2000	N	—	—	0.6*	3
17. Rai-Iz, Urals, Russian Federation	Devi et al. (2008)	144	1700–2002	E	UA	BC	0.3	35*
18. Sahel, Sudan, Guinea zones; Senegal	Gonzalez (2001)	135	1945–1993	L	RW	RG	0.4*	–48*
19. Sahel, Burkina Faso, Chad, Mali, Mauritania, Niger	Gonzalez et al. (2012)	14	1960–2000	L	RW	RG	–0.01* to 0.8*	–31* to 9
20. Scandes, Sweden	Kullman and Öberg (2009)	123	1915–2007	E	UA	BC	0.8*	25*
21. Sierra Nevada, California, USA	Millar et al. (2004)	10	1880–2002	E	UA	TC	–0.1	21*
22. South Island, New Zealand	Wardle and Coleman (1992)	22	1980–1990	E	TS	TB	0.6*	3
23. Yambarran, Northern Territory, Australia	Sharp and Bowman (2004)	33	1948–2000	N	—	—	–0.06	35*

carbon cycle, and associated feedbacks and services have responded to this climatic change, particularly when the climatic change was as large as that projected during the 21st century under mid- to high-end radiative forcing pathways (e.g., MacDonald et al., 2008; Claussen, 2009; Arneith et al., 2010; Dawson et al., 2011; Willis and MacDonald, 2011). Excellent examples of past large climate change events that drove large ecological change, as well as recovery periods in excess of a million years, include the events that led to the Earth's five mass extinctions in the distant past (i.e., during the Ordovician, about 443 Ma, the Devonian, about 359 Ma, the Permian, about 251 Ma, the Triassic, about 200 Ma, and the Cretaceous, about 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; Wing and Currano, 2013), the early Eocene Climatic Optimum (EECO, 53 to 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) to Holocene transition between 21 and 6 ka (MacDonald et al., 2008; Clark et al., 2009; Gill et al., 2009; Williams, J.W. et al., 2010; Prentice et al., 2011; Daniiau et al., 2012). The paleoecological record thus provides *high confidence* that large global climate change, comparable in magnitude to that projected for the 21st century, can result in large

ecological changes, including large-scale biome shifts, reshuffling of communities, and species extinctions.

Rapid, regional warming before and after the Younger Dryas cooling event (11.7 to 12.9 ka) provides a relatively recent analogy for climate change at a rate approaching, for many regions, that projected for the 21st century for all Representative Concentration Pathways (RCPs; Alley et al., 2003; Steffensen et al., 2008). Ecosystems and species responded rapidly during the Younger Dryas by shifting distributions and abundances, and there were some notable large animal extinctions, probably exacerbated by human activities (Gill et al., 2009; Dawson et al., 2011). In some regions, species became locally or regionally extinct (extirpated), but there is no evidence for climate-driven global-scale extinctions during this period (Botkin et al., 2007; Willis, K.J. et al., 2010). However, the Younger Dryas climate changes 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, about 6 ka, provides a very recent example of the effects of modest climate change. Regional mean warming during this period (mean annual temperature about 0.5°C to 1.0°C above



4

Figure 4-2 | Projections of climate change-driven biome shifts in the context of direct human land use. (a) Fraction of land covered by primary vegetation in 2005 (Hurt et al., 2011); (b) Fraction of land covered by primary vegetation in 2100 under the RCP2.6 land use scenario, with no effect of climate change (Hurt et al., 2011); (c) Fraction of land covered by primary vegetation in 2100 under the RCP6.0 land use scenario, with no effect of climate change (Hurt et al., 2011). (d) Fraction of simulations showing climate change-driven biome shift for any level of global warming between 1990 and 2100, with no direct anthropogenic land use change, using the MC1 vegetation model under 9 CMIP3 climate projections (3 GCMs, each forced by the SRES A2, A1B, and B1 scenarios; Gonzalez et al., 2010); Comparison of colored areas in (d) with those in (a) shows where climate-driven biome shifts would occur in current areas of primary vegetation. Comparison of (b) and (c) with (a) illustrates two scenarios of how primary vegetation could change due to direct human land use, irrespective of the effects of climate change. (b) shows the land use scenario associated with RCP2.6, in which global climate change is projected to be smaller than that driving the biome shifts in (d) as a result of mitigation measures, some of which involved land use. (c) shows the land use scenario associated with RCP6.0, in which global climate change is projected to be larger than RCP2.6 so biome shifts similar to those in (d) may occur alongside the projected land use changes in (c). For example, climate change-driven biome shift is projected in many Arctic land areas (d) which are unaffected by direct human land use at the present day (a) and in the RCP2.6 and 6.0 land use scenarios (b, c), indicating that climate change is the dominant influence on Arctic land ecosystems in these scenarios. In contrast, in Borneo, none of the GCMs analysed by Gonzalez et al. (2010) project climate change-driven biome shift (d), and instead a reduction in primary vegetation cover occurs in the mitigation scenario RCP2.6 as a consequence of direct human land use (b). A smaller reduction occurs in RCP6.0. Land use is therefore projected to be the dominant driver of change in Borneo in these scenarios. In the boreal forest regions of North America, Europe, and north-west Asia, climate change-driven biome shift (d) is projected in regions already subject to some influence of present-day human land use (a), and increased land use leading to further reductions in primary vegetation occur in both RCP2.6 (b) and RCP6.0 (c). Hence in these boreal forest regions, both climate change and land use are projected to be drivers of ecosystem change in these scenarios. Further details of the RCP land use/cover scenarios are given in Box 4-1, Figure 4-3, and Table 4-2.

preindustrial in some continental-scale regions; see WGI AR5 Section 5.5.1) was the same order of magnitude as the warming the Earth has experienced over the 20th century. Ecological effects were small compared to periods with larger climate excursions, but even this small warming was characterized by frequent fires in drier parts of the Amazon (Mayle and Power, 2008), development of lush vegetation and lakes in a wetter Sahara (Watrín et al., 2009), temperate deciduous forests in Europe expanding further north and up to higher elevations (Prentice et al., 1996), 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, also clearly impacted inland water systems (e.g., Smol and Douglas, 2007a; Battarbee et al., 2009; Beilman et al., 2009). However, there are no exact analogs 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 and atmospheric carbon dioxide (CO₂) change projected for the 21st century and beyond (Jansen et al., 2007; Schulte et al., 2010; Wing and Currano, 2013; see WGI 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* that these interactions will 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 the 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 vegetation to large paleoclimate change (Prentice et al., 1996, 2011; Salzmann et al., 2008). The same types of models predict large changes in species ranges, ecosystem function, and carbon storage when forced by 21st century climate change, although the future situation is complicated by land use and other factors absent in the paleoenvironmental case (Sitch et al., 2008; Cheaib et al., 2012; see WGI AR5 Section 6.4). Thus, the paleoecological record and models that have been tested against it provide a coherent message that biomes will alter their functioning and composition in response to changing and often novel future climates: they will move as species mixtures change (Section 4.3.2.5 has more specific information on projected migration rates), novel plant communities will emerge, and significant carbon stock changes will take place (Williams and Jackson, 2007; MacDonald, 2010; Prentice et al., 2011;

Willis and MacDonald, 2011). The paleoecological record and models provide *high confidence* that it will be difficult or impossible to maintain many ecological systems in their current states if global warming exceeds 2°C to 3°C, raising questions about the long-term viability of some current protected areas and conservation schemes, particularly where the objective is to maintain present-day species mixtures (Jackson and Hobbs, 2009; Hickler et al., 2012).

Much of the complex, time-dependent change at regional scales has not yet been simulated by models. The paleoecological record indicates that vegetation in many parts of the world has the potential to respond within years to a few decades to climate change (e.g., Mueller, A.D. et al., 2009; Watrín et al., 2009; Williams et al., 2009; Harrison and Goni, 2010). This record provides a critical opportunity for model evaluation that should be more thoroughly exploited to gain confidence in time-dependent simulations of future change, particularly given the complex role that interacting climate change and vegetation disturbance has played in the past (e.g., Jackson et al., 2009; Marlon et al., 2009; Williams et al., 2009; Daniau et al., 2010; Dawson et al., 2011). The paleoecological record also highlights the importance of including the direct effects of changing atmospheric CO₂ levels in efforts to simulate future ecosystem functioning and plant species competition (Prentice et al., 2011; Woillez et al., 2011; Bond and Midgley, 2012; Claussen et al., 2013).

The paleoclimatic record also reveals that past radiative climate forcing change was slower than that anticipated for the 21st century (see WGI AR5 Chapters 5, 8, and 12), but even these slower changes often drove surprisingly abrupt, nonlinear, regional-scale change in terrestrial and inland water systems (e.g., Harrison and Goni, 2010; Williams et al., 2011), as did even slower climate change during the most recent Holocene interglacial (e.g., Booth et al., 2005; Kropelin et al., 2008; Williams, J.W. et al., 2010; Williams et al., 2011). In all cases, specific periods of abrupt ecological response were regionally distinct in nature and were less synchronous for small, slow changes in forcing (e.g., during the Holocene) than for the global-scale rapid changes listed at the start of this section. State-of-the-art climate and Earth System Models (ESMs) are unable to simulate the full range of abrupt change observed in many of these periods (e.g., Valdes, 2011). Thus there is *high confidence* that these models may not capture some aspects of future abrupt climate change and associated ecosystem impacts (Leadley et al., 2010).

Frequently Asked Questions

FAQ 4.1 | How do land use and land cover changes cause changes in climate?

Land use change affects the local as well as the global climate. Different forms of land cover and land use can cause warming or cooling and changes in rainfall, depending on where they occur in the world, what the preceding land cover was, and how the land is now managed. Vegetation cover, species composition, and land management practices (such as harvesting, burning, fertilizing, grazing, or cultivation) influence the emission or absorption of greenhouse gases. The brightness of the land cover affects the fraction of solar radiation that is reflected back into the sky, instead of being absorbed, thus warming the air immediately above the surface. Vegetation and land use patterns also influence water use and evapotranspiration, which alter local climate conditions. Effective land use strategies can also help to mitigate climate change.

4.2.4. Multiple Stressors Interacting with Climate Change

The climatic and non-climatic drivers of ecosystem change need to be distinguished if the joint and separate attribution of changes to their causes is to be performed (see Chapter 18). In this section we elaborate on factors affecting ecosystems, operating simultaneously with climate change. These factors share underlining drivers with one another and with climate change to varying degrees; together they form a syndrome known as “global change.” The individual effects of climate change, habitat loss and fragmentation, chemical pollution, overharvesting, and invasive alien species are increasingly well documented (Millennium Ecosystem Assessment, 2005c; Settele et al., 2010a) but much less is known about their combined consequences. Ecosystem changes may occur in cascades, where a change in one factor precipitates increased vulnerability with respect to other factors (Wookey et al., 2009) or propagates through the ecosystem as a result of species interactions (Gilman et al., 2010). Multiple stressors can act in a non-additive way (Shaw et al., 2002; Settele et al., 2010b; Larsen et al., 2011), potentially invalidating findings and interventions based on single-factor analysis. For instance, Larsen et al. (2011) demonstrated that non-additive interactions among the climate factors in a multifactor experiment were frequent and most often antagonistic, leading to smaller effects than predicted from the sum of single factor effects. Leuzinger et al. (2011) and Dieleman et al. (2012) have synthesized multifactor experiments and demonstrated that, in general, the effect size is reduced when more factors are involved, but Leuzinger et al. (2011) suggest that multifactor models tend to show the opposite tendency.

4.2.4.1. Land Use and Cover Change

Land use and cover change (LUCC) is both a cause (WGI AR5 Section 6.1.2) and a consequence of climate change. It is the major driver of current ecosystem and biodiversity change (Millennium Ecosystem Assessment, 2005b) and a key cause of changes in freshwater systems (Section 4.3.3.3). In tropical and subtropical areas of Asia, Africa, Oceania, and South America, the dominant contemporary changes are conversion of forests and woodlands to annual and perennial agriculture, grazing pastures, industrial logging, and commercial plantations, followed by conversion of savannas, grasslands, and pastures to annual agriculture (Hosonuma et al., 2012; Macedo et al., 2012). In Europe there is net conversion of agricultural lands to forest (Rounsevell and Reay, 2009; Miyake et al., 2012). Conversion of peatlands to agriculture has been an important source of carbon to the atmosphere in Southeast Asia (Limpens et al., 2008; Hooijer et al., 2010; see Section 4.3.3.3).

Contemporary drivers of LUCC include rising demand for food, fiber, and bioenergy and changes in lifestyle and technologies (Hosonuma et al., 2012; Macedo et al., 2012). By mid-century climate change is projected to become a major driver of land cover change (Leadley et al., 2010). Non-climate environmental changes such as nitrogen deposition, air pollution, and altered disturbance regimes are also implicated in LUCC. Some of the underlying drivers of LUCC are also direct or indirect drivers of climate change (Cui and Graf, 2009; McAlpine et al., 2009; Mishra et al., 2010; Schwaiger and Bird, 2010; van der Molen et al., 2011; Groisman et al., 2012); this cause-and-effect entanglement of climate change and LUCC can confound the detection of climate change and make attribution

to one or the other difficult. Local-to-regional climate change was at least partly attributed to LUCC in 11 of 26 studies reviewed for this chapter, generally with *limited evidence* and *low confidence*. (Direct climate effects attributed to LUCC: Cui and Graf, 2009; Li et al., 2009; McAlpine et al., 2009; Zhang et al., 2009; Fall et al., 2010; Jin et al., 2010; Mishra et al., 2010; Schwaiger and Bird, 2010; Wu et al., 2010; Carmo et al., 2012; Groisman et al., 2012. No climate effects studied: Suarez et al., 1999; Saurral et al., 2008; Tseng and Chen, 2008; Wang et al., 2008; Cochrane and Barber, 2009; Jia, B. et al., 2009; Rounsevell and Reay, 2009; Graiprab et al., 2010; Martin et al., 2010; Wiley et al., 2010; Clavero et al., 2011; Dai et al., 2011; Gao and Liu, 2011; Viglizzo et al., 2011; Yoshikawa and Sanga-Ngoie, 2011).

LUCC (and land use itself) contributes to changes in the climate through altering the GHG concentrations in the atmosphere, surface and cloud albedos, surface energy balance, wind profiles, and evapotranspiration, among other mechanisms. The phrase “biophysical effects” is shorthand for the effect vegetation has on the climate other than through its role as a source or sink of GHGs. These effects are now well documented, significant, and are increasingly included in models of global and regional climate change. The GHG and biophysical effects of vegetation can be opposite in sign (de Noblet-Ducoudre et al., 2012) and operate at different scales. For instance, conversion of forest to non-forest generally releases CO₂ from biomass and soils to the atmosphere (causing warming globally), but may result in an increase in seasonally averaged albedo (local and global cooling, Davin et al., 2007) and a decrease in transpiration (local, but not global warming). Findell et al. (2007) concluded on the basis of model studies that the non-GHG climate impacts of LUCC were generally minor, but nevertheless significant in some regions. Brovkin et al. (2013), projecting the overall effect of LUCC on climate change for the 21st century, found LUCC to be a small driver globally, but locally important. Most global climate models suggest local average cooling effects following forest conversion to croplands and pastures (Pitman et al., 2009; Longobardi et al., 2012). Satellite observations suggest that the effect of conversion of the Brazilian savannas (*cerrado*) to pasture was to induce a local warming that was partly reversed when the pasture was subsequently converted to sugarcane (Loarie et al., 2011). Several modeling studies suggest that the global surface air temperature response to deforestation depends on the latitude at which deforestation occurs. High-latitude deforestation results in global cooling, low-latitude deforestation causes global warming, and the mid-latitude response is mixed (Bathiany et al., 2010; Davin and de Noblet-Ducoudre, 2010; van der Molen et al., 2011; Longobardi et al., 2012), with some exceptions documented for boreal forests (Spracklen et al., 2008). Boreal and tropical forests influence the climate for different reasons: boreal forests have low albedo (i.e., reflect less solar radiation, especially in relation to a snowy background; Levis, 2010; Mishra et al., 2010; Longobardi et al., 2012) and tropical forests pump more water and aerosols into the atmosphere than non-forest systems in similar climates (Davin and de Noblet-Ducoudre, 2010; Delire et al., 2011; Pielke et al., 2011). The implications of these findings for afforestation as a climate mitigation action are discussed in Section 4.3.4.5. Forests may also influence regional precipitation through biophysical effects (Butt et al., 2011; Pielke et al., 2011; see Section 4.3.3).

In summary, changes in land cover have biophysical effects on the climate, sometimes opposite in direction to GHG-mediated effects,

Box 4-1 | Future Land Use Changes

Assessment of climate change effects on terrestrial and inland freshwater ecosystems requires the simultaneous consideration of land use and cover change (LUCC). The world is undergoing important shifts in land use, driven by accelerating demand for food, feed, fiber, and fuel. The main underlying driver is the rate at which per capita consumption is growing, particularly in emerging economies (Tilman et al., 2011). Policy shifts in developed countries favoring biofuel production have also contributed (Searchinger et al., 2008; Lapola et al., 2010; Miyake et al., 2012). Agricultural commodity prices have risen and may stay high through 2020 (OECD and FAO, 2010), owing to (1) demand growth outpacing supply growth, exacerbated by climate-related crop failure (Lobell et al., 2011); (2) decline in the rate of improvement in agricultural productivity (Ray et al., 2012); (3) shortage of arable land not already under cultivation, especially in the temperate zone; (4) growing pressure on as-yet uncultivated ecosystems on soils that are potentially suitable for cultivation and that are concentrated in tropical latitudes, especially South America and Africa (Lambin and Meyfroidt, 2011); and (5) declining area under cultivation in temperate zones, mainly in developed countries. The shortage of arable land in temperate systems could put pressure on marginal or sensitive landscapes, mainly in Latin America's *cerrados* and grasslands (Brazil, Argentina) and in African savannas (Sudan, Democratic Republic of Congo, Mozambique, Tanzania, Madagascar) (Lambin and Meyfroidt, 2011).

Deforestation in developing countries correlates with the export of agricultural commodities (DeFries et al., 2010). Future LUCC remains uncertain, as it depends on economic trends and policies themselves dependent on complex political and social processes, including climate policy. By 2100, the deforestation rate in the Brazilian Amazon had declined by 77% below its 1996–2005 average (Nepstad et al., 2009; INPE, 2013) as a result of policy and market signals (Soares-Filho et al., 2010). This single trend represents a 1.5% reduction in global anthropogenic carbon emissions (Nepstad et al., 2013).

Table 4-2 | Summary of drivers and outcomes of Land Use and Land Cover Change (LUCC) scenarios associated with Representative Concentration Pathways (RCPs; Hurtt et al., 2011). RCPs are identified with the radiative forcing by 2100 (8.5, 6.0, 4.5, and 2.6 W m⁻²) and by the name of the model used to generate the associated land use/cover scenarios (MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact), AIM (Asia-Pacific Integrated Model), GCAM (Global Change Assessment Model), and IMAGE (Integrated Model to Assess the Global Environment); see Hurtt et al. (2011) for further details).

RCP	Model and references	Key assumptions/drivers	Land use/cover outcomes
8.5	MESSAGE; Riahi et al. (2007)	<ul style="list-style-type: none"> No climate change mitigation actions; radiative forcing still rising at 2100. Strong increase in agricultural resource use driven by the increasing population (rises to 12 billion people by 2100). Yield improvements and intensification assumed to account for most of production increases. 	<ul style="list-style-type: none"> Increase in cultivated land by about 305 million ha from 2000 to 2100. Forest cover declines by 450 million ha from 2000 to 2100. Arable land use in developed countries slightly decreased — all of the net increases occur in developing countries.
6.0	AIM; Fujino et al. (2006), Hijioka et al. (2008)	<ul style="list-style-type: none"> Mitigation actions taken late in the century to stabilize radiative forcing at 6 W m⁻² after 2100. Population growth and economic growth. Increasing food demand drives cropland expansion. 	<ul style="list-style-type: none"> Urban land use increases. Cropland area expands. Grassland area declines. Total forested area extent remains constant.
4.5	GCAM; Smith and Wigley (2006), Wise et al. (2009)	<ul style="list-style-type: none"> Mitigation stabilizes radiative forcing at 4.5 W m⁻² before 2100. Assumes that global greenhouse gas emissions prices are invoked to limit emissions and therefore radiative forcing. Emissions pricing assumes all carbon emissions are charged an equal penalty price, so reductions in land use change carbon emissions available as mitigation. Food demand is met through crop yield improvements, dietary shifts, production efficiency, and international trade. 	<ul style="list-style-type: none"> Preservation of large stocks of terrestrial carbon in forests. Overall expansion in forested area. Agricultural land declines slightly due to afforestation.
2.6	IMAGE; van Vuuren et al. (2006), van Vuuren et al. (2007)	<ul style="list-style-type: none"> Overall trends in land use and land cover are determined mainly by demand, trade, and production of agricultural products and bioenergy. Expansion of croplands largely due to bioenergy production. Production of animal products is met through shift from extensive to more intensive animal husbandry. 	<ul style="list-style-type: none"> Much agriculture relocates from high-income to low-income regions. Increase in bioenergy production, new area for bioenergy crops near current agricultural areas. Pasture largely constant.

Continued next page →

Box 4-1 (continued)

Each of the four main Representative Concentration Pathways (RCPs) used for future climate projections has a spatially explicit future land use scenario consistent with both the emissions scenario and the underlying associated socioeconomic scenario simulated by integrated assessment models, as well as conditions in 2005 (Hurtt et al., 2011; see also Table 4-2, Figure 4-2, Figure 4-3). In scenarios where cropland and pasture are projected to decrease, they are replaced with secondary vegetation. Tropical and boreal forest regions are both projected to undergo declining primary forest cover in most RCPs, but in RCP6.0 total forest area remains approximately constant and in RCP4.5 total forest area expands because of increased secondary forest. The extent to which primary vegetation is replaced by secondary vegetation, crops, or pasture varies between the RCPs (Figure 4-3), with no simple linear relationship between the extent of vegetation change and the level of total radiative forcing. Larger reductions in primary vegetation cover are projected in RCP8.5, owing to a general absence of proactive measures to control land cover change in that scenario. Large reductions are also projected in RCP2.6 owing to widespread conversion of land to biofuel crops (Figure 4-2). Smaller reductions are foreseen in RCP6.0 and RCP4.5, with the latter involving conservation of primary forest and afforestation as mitigation measures.

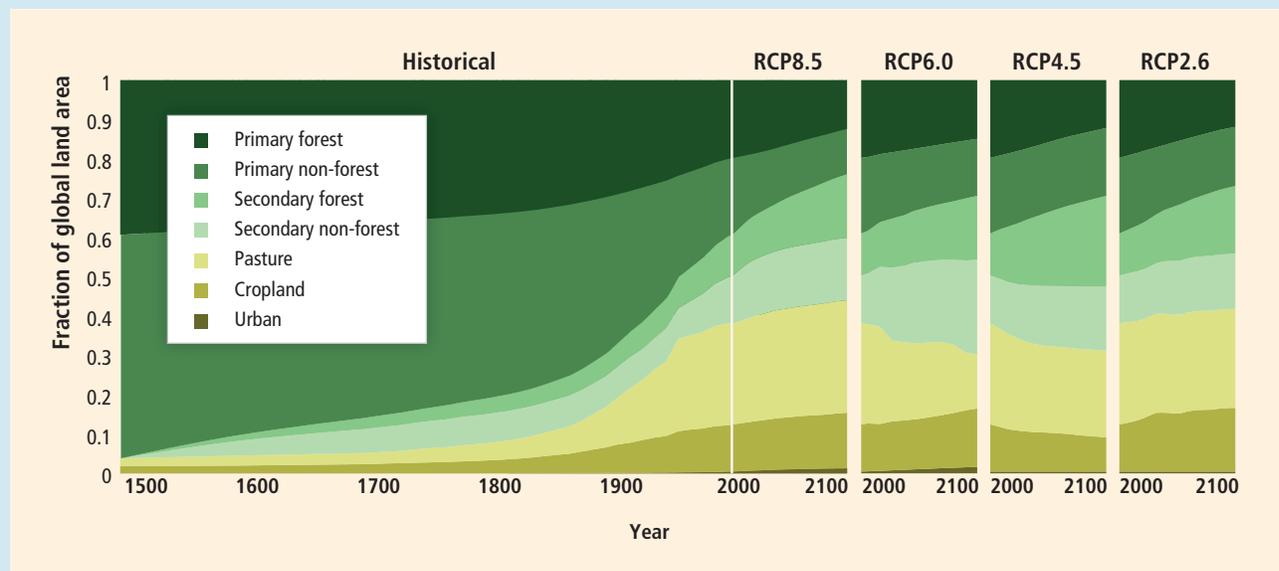


Figure 4-3 | Proportion of global land cover occupied by primary and secondary vegetation (forest and non-forest), cropland, pasture, and urban land, from satellite data and historical reconstructions up to 2005 (Klein Goldewijk et al., 2010, 2011), and from scenarios associated with the RCPs from 2005 to 2100 (Hurtt et al., 2011).

which can materially alter the net outcome of the land cover change on the global climate (*high confidence*).

4.2.4.2. Nitrogen Deposition

The global nitrogen cycle has been strongly perturbed by human activity over the past century (Gruber and Galloway, 2008; Canfield et al., 2010). Activities such as fertilizer production and fossil fuel burning currently transform 210 TgN yr^{-1} of nitrogen gas in the atmosphere into reactive forms of nitrogen (N_x) that can be readily used by plants and microorganisms in land and in the ocean, slightly more than the non-anthropogenic transformation of 203 TgN yr^{-1} (Fowler et al., 2013). Most of the transformations of anthropogenic N_x are on land (Fowler et al., 2013). The human-caused flow from land to oceans in rivers is 40 to 70 TgN yr^{-1} , additional to the estimated natural flux of 30 TgN yr^{-1}

(Galloway et al., 2008; Fowler et al., 2013). Many of the sources of additional nitrogen share root causes with changes in the carbon cycle, such as increased use of fossil fuels and expansion and intensification of global agriculture. Nitrogen deposition, CO_2 concentrations, and temperatures are therefore increasing together at global scales (Steffen et al., 2011). Regional trends in nitrogen fluxes differ substantially: nitrogen fertilizer use and nitrogen deposition are stable or declining in some regions, such as Western Europe; but nitrogen deposition and its impacts on biodiversity and ecosystem functioning are projected to increase substantially over the next several decades in other regions, especially in the tropics (Galloway et al., 2008) owing to increased needs for food and energy for growing populations in emerging economies (e.g., Zhu et al., 2005).

Experiments and observations, most of which are in temperate and boreal Europe and North America, show a consistent pattern of increase in the

dominance of a few nitrogen-loving plant species and loss of overall plant species richness at nitrogen deposition loads exceeding between 5 and 20 kgN ha⁻¹ yr⁻¹ (Power et al., 2006; Clark and Tilman, 2008; Bobbink et al., 2010; but see Stevens, C.J. et al., 2010). Nitrogen deposition is currently above these limits in much of Europe, eastern North America, and southern Asia (Galloway et al., 2008), including in many protected areas (Bleeker et al., 2011).

The impacts of nitrogen deposition are often first manifested in freshwater ecosystems because they collect and concentrate the excess nitrogen (and phosphorus) from the land, as well as from sewage and industrial effluents. Primary production in freshwater ecosystems can be either nitrogen and phosphorus limited or both (Elser et al., 2007), but the biodiversity and capacity of freshwater ecosystems to deliver high-quality water, recreational amenity, and fisheries services is severely reduced by the addition of nutrients beyond their capacity to process them. Excessive loading of nitrogen and phosphorus is widespread in the lakes of the Northern Hemisphere (NH; Bergström and Jansson, 2006), although reduced nitrogen loading including deposition was observed between 1988 and 2003 in Sweden (Weyhenmeyer et al., 2007). The observed symptoms include a shift from nitrogen limitation of phytoplankton in lakes to phosphorus limitation (Elser et al., 2009).

Since the AR4, an increasing number of studies have models, observations, and experiments to understand and predict the interactive effects of nitrogen deposition, climate change, and CO₂ on ecosystem function. Interactions between nitrogen and other global change factors are widespread, strong, and complex (Rustad, 2008; Thompson et al., 2008; Langley and Magonigal, 2010; Gaudnik et al., 2011; Eisenhauer et al., 2012; Hoover et al., 2012; but see Zavaleta et al., 2003, for evidence of additive effects). In a study of plant-pollinator relationships, the combination of nitrogen deposition, CO₂ enrichment, and warming resulted in larger negative impacts on pollinator populations than could be predicted from the individual effects (Hoover et al., 2012). In a perennial grassland species, nitrogen limitation constrained the response to rising CO₂ (Reich et al., 2006). Broadly, the overall body of research shows that ecosystem function is mediated by complex interactions between these factors, such that many ecosystem responses remain difficult to understand and predict (Churkina et al., 2010; Norby and Zak, 2011).

In forests in many parts of the world, experiments, observations, and models suggest that the observed increase in productivity and carbon storage is due to combinations of nitrogen deposition, climate change, fertilization effects of rising CO₂, and forest management (Huang et al., 2007; Magnani et al., 2007; Pan et al., 2009; Churkina et al., 2010; Bellassen et al., 2011; Bontemps et al., 2011; de Vries and Posch, 2011; Eastaugh et al., 2011; Norby and Zak, 2011; Shanin et al., 2011; Lu et al., 2012). N deposition and rising CO₂ appear to have generally dominated in much of the NH. However, the direct effects of rising temperature and changes in precipitation may exceed nitrogen and CO₂ as key drivers of ecosystem primary productivity in a few decades time. In grasslands, however, experiments show that plant productivity is increased more by nitrogen addition (within the projected range for this century) than by elevated CO₂, also within its projected range, and that nitrogen effects increase with increasing precipitation (Lee et al., 2010).

In contrast to forests and temperate grasslands, nitrogen deposition and warming can have negative effects on productivity in other terrestrial ecosystems, such as moss-dominated ecosystems (Limpens et al., 2011). The interactions between nitrogen deposition and climate change remain difficult to understand and predict (Menge and Field, 2007; Ma et al., 2011), in part owing to shifts in plant species composition (Langley and Magonigal, 2010) and the complex dynamics of coupled carbon, nitrogen, and phosphorus cycles (Menge and Field, 2007; Niboyet et al., 2011).

Analyses using the multi-factor biodiversity change model GLOBIO3 suggest that nitrogen deposition will continue to be a significant contributing factor to terrestrial biodiversity loss in the first third of the 21st century but will be a less important factor than climate change in this period, and a much smaller driver than habitat loss due to expansion of agricultural lands (Alkemade et al., 2009). Models that explicitly take into account interactive effects of climate change and nitrogen deposition on plant communities project that nitrogen deposition impacts will continue to be important, but climate change effects will begin to dominate other factors by the middle of the 21st century (Belyazid et al., 2011).

4.2.4.3. Tropospheric Ozone

The concentration of ozone in the troposphere (the part of the atmosphere adjacent to the Earth's surface) has risen over the past 150 years from a global average of 20 to 30 ppb to 30 to 50 ppb, with high spatial and temporal variability (Horowitz, 2006; Oltmans et al., 2006; Cooper et al., 2010; WGI AR5 Figure 2.7). This is due to (1) increasing anthropogenic emissions of gases that react in the atmosphere to form ozone (Denman et al., 2007) and (2) 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 (VOCs) and oxides of nitrogen (NO_x). Intercontinental transport of these precursors contributes to rising global background ozone concentrations, including in regions where local ozone precursor emissions are decreasing (Dentener et al., 2010). Global sources of VOC are predominantly biogenic (BVOC), especially forests (Hoyle et al., 2011).

Negative effects of the current levels of ozone have been widely documented (Mills et al., 2011). A meta-analysis of more than 300 articles addressing the effect of ozone on tree growth (Wittig et al., 2009)—focused largely on NH temperate and boreal species—concluded that current levels of tropospheric ozone suppress growth by 7% relative to preindustrial levels. Modeling studies that extrapolate experimentally measured dose-response relationships suggest a 14 to 23% contemporary reduction in Gross Primary Productivity (GPP) worldwide, with higher values in some regions (Sitch et al., 2007) and 1 to 16% reduction of Net Primary Productivity (NPP) in temperate forests (Ainsworth et al., 2012).

The mechanisms by which ozone (O₃) affects plant growth are now better known (Hayes et al., 2007; Ainsworth et al., 2012). Chronic exposure to O₃ at levels above about 40 ppb generally reduces stomatal conductance and impairs the activity of photosynthetic enzymes (The Royal Society, 2008), although in some cases ozone exposure increases stomatal conductance (Wilkinson and Davies, 2010). For the species studied,

carbon assimilation rates and leaf area are generally reduced, while respiration increases and leaf senescence is accelerated—all leading to a reduction in NPP. Conifers are less sensitive than broad-leafed species. In a modeling study, lower stomatal conductance due to O₃ exposure increased river runoff by reducing the loss of soil moisture through transpiration, but observational studies that measured runoff in relation to ozone exposure show divergent trends on this issue (McLaughlin et al., 2007; Wittig 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 O₃ on plant productivity could offset 17 to 31% of the projected increase in global carbon storage due to increasing CO₂ concentrations over the 21st century, but the possible interactive effects between CO₂ and O₃ are poorly understood (The Royal Society, 2008). Reduced stomatal conductance, widely observed under elevated CO₂, 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 study of CO₂ and O₃ interactions in a temperate forest (Karnosky et al., 2005; Hofmockel et al., 2011) suggests that the effects of O₃ and CO₂ are not independent and may partly compensate for one another.

There is genotypic variation in plant sensitivity to O₃ (Ainsworth et al., 2012). Other than changing cultivars or species, few management actions promoting adaptation to higher levels of O₃ are currently available (Wilkinson and Davies, 2010; Teixeira et al., 2011). Research into developing ozone resistant varieties and chemical protectants against damage may provide management options in the future (Wilkinson and Davies, 2010; Ainsworth et al., 2012).

4.2.4.4. Rising Carbon Dioxide

Rising atmospheric CO₂ concentrations affect ecosystems directly and through biological and chemical processes. The consequences for the global carbon cycle are discussed in WGI AR5 Box 6.3; the discussion here focusses on impacts on terrestrial and inland water systems. Paleo records over the Late Quaternary (past Myr) show that changes in the atmospheric CO₂ content between 180 and 280 ppmv had ecosystem-scale effects worldwide (Prentice and Harrison, 2009).

In contrast to the oceans, changes in CO₂ concentrations in inland waters are influenced primarily by biological processes, such as inputs

of terrestrial organic matter, particularly dissolved organic carbon (DOC), and bacterial respiration (van de Waal et al., 2010; Aufdenkampe et al., 2011). Carbon can, however, become limiting during intense algal blooms, especially in the surface waters of stratified lakes and reservoirs, and rising atmospheric CO₂ concentrations may stimulate higher algal production under these conditions (van de Waal et al., 2010). Higher CO₂ concentrations can lead to increases in the C:N and C:P ratios of phytoplankton, though the trophic consequences of this are difficult to predict because zooplankton may alter their feeding behavior to select higher quality forms of algae or increase feeding rate (Urabe et al., 2003; van de Waal et al., 2010).

Over the past 2 decades, and especially since AR4, experimental investigation of elevated CO₂ effects on plants and ecosystems has used mainly Free Air CO₂ Enrichment (FACE) techniques (Leakey et al., 2009). FACE is 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. Plants with a C₃ photosynthetic system, which includes most species but excludes warm-region grasses, show an increase in photosynthesis under elevated CO₂, the precise magnitude of which varies between species. Acclimation (“down-regulation”) occurs under long-term exposure, leading to cessation of effects in some (Norby and Zak, 2011) but not all studies (Leakey et al., 2009). The C₄ photosynthetic system found in most tropical grasses and some important crops is not directly affected by elevated CO₂, but C₄ plant productivity generally increases under elevated CO₂ because of increased water use efficiency (WUE). Transpiration is decreased under elevated CO₂ in many species, due to reduced opening of stomatal apertures, leading to greater WUE (Leakey et al., 2009; Leuzinger and Körner, 2010; De Kauwe et al., 2013). Increasing WUE is corroborated by studies of stable carbon isotopes (Barbosa et al., 2010; Koehler et al., 2010; Silva et al., 2010; Maseyk et al., 2011). The WUE increase does not acclimate to higher CO₂ in the medium term, that is, over several years (Leakey et al., 2009). Satellite observations from 1982–2010 show an 11% increase in green foliage cover in warm, arid environments (where WUE is most important) after correcting for the effects of precipitation variability (Donohue et al., 2013); gas exchange theory predicts 5 to 10% greening resulting from rising CO₂ over this period.

The interactive effects of elevated CO₂ and other global changes (such as climate change, nitrogen deposition, and biodiversity loss) on ecosystem function are extremely complex. Generally, nitrogen use efficiency is

Frequently Asked Questions

FAQ 4.2 | What are the non-greenhouse gas effects of rising carbon dioxide on ecosystems?

Carbon dioxide (CO₂) is an essential building block of the process of photosynthesis. Simply put, plants use sunlight and water to convert CO₂ into energy. Higher CO₂ concentrations enhance photosynthesis and growth (up to a point), and reduce the water used by the plant. This means that water remains longer in the soil or recharges rivers and aquifers. These effects are mostly beneficial; however, high CO₂ also has negative effects, in addition to causing global warming. High CO₂ levels cause the nitrogen content of forest vegetation to decline and can increase their chemical defenses, reducing their quality as a source of food for plant-eating animals. Furthermore, rising CO₂ causes ocean waters to become acidic (see FAQ 6.3), and can stimulate more intense algal blooms in lakes and reservoirs.

increased under higher CO₂ (Leakey et al., 2009) although, in some tree FACE experiments, productivity increases as a result of enhanced CO₂ if sustained by increased nitrogen uptake rather than increased nitrogen use efficiency (Finzi et al., 2007). In one 10-year temperate grassland experiment in Minnesota, elevated CO₂ halved the loss of species richness expected from nitrogen addition (Reich, 2009), whereas no such benefit was reported for an alpine grassland in France (Bloor et al., 2010) or a Danish heathland ecosystem (Kongstad et al., 2012).

Elevated CO₂ can affect plant response to other stresses, such as high temperature (Lloyd and Farquhar, 2008) and drought. Ozone exposure decreases with lower stomatal conductance (Sitch et al., 2007). In savannas, faster growth rates under higher CO₂ can allow woody plants to grow tall enough between successive fires to escape the flames (Bond and Midgley, 2001; Scheiter and Higgins, 2009). Differential species responses to elevated CO₂ appear to be altering competition (Dawes et al., 2011), for example, increasing the likelihood of faster-growing species such as lianas out-competing slower-growing species such as trees (Mohan et al., 2006; Potvin et al., 2007; Lewis et al., 2009a).

Experimental studies have shown that elevated CO₂ leads to increased leaf C:N ratios in woody plants, forbs, and C₃ grasses (but not C₄ grasses), which may decrease their quality as food and increase herbivorous insect feeding rates and changes to their density and community structure (Sardans et al., 2012). Plants may also become more toxic to herbivores under elevated CO₂ levels, through increased concentrations of carbon- and nitrogen-based defenses (Lindroth, 2010; Cavagnaro et al., 2011).

Our understanding of ecosystem responses to elevated CO₂ is incomplete in some respects. The majority of FACE experiments apply upper CO₂ concentrations of approximately 550 ppmv, which is below the concentrations projected by 2100 under higher emissions scenarios. The physiology of photosynthesis suggests that direct CO₂ effects saturate at levels of approximately 700 ppmv (Long et al., 2004). Most elevated CO₂ experiments impose a sudden increase of CO₂ concentration as opposed to the gradual rise experienced in reality. Most large-scale FACE experiments have been conducted in temperate locations (e.g., Hickler et al., 2008); there are currently no large-scale tropical or boreal FACE experiments. The magnitude of CO₂ effects decreases as the spatial scale of study increases (Leuzinger et al., 2011). The scale of controlled experiments is limited to approximately 100 m². Extrapolation to larger scales ignores large-scale atmospheric feedbacks (Körner et al., 2007) and catchment-scale hydrological effects (see Box CC-VW). Overall, there is *medium confidence (much evidence, medium agreement)* that increases in CO₂ up to about 600 ppm will continue to enhance photosynthesis and plant water use efficiency, but at a diminishing rate.

CO₂ effects are a first-order influence on model projections of ecosystem and hydrological responses to anthropogenic climate change (Sitch et al., 2008; Lapola et al., 2009; Friend et al., 2013). The direct effect of CO₂ on plant physiology, independent of its role as a GHG, means that assessing climate change impacts on ecosystems and hydrology solely in terms of global mean temperature rise (or equivalently, expressing GHG effects solely in terms of radiative forcing) is an oversimplification (Huntingford et al., 2011; Betts et al., 2012). A 2°C rise in global mean temperature, for example, may have a different net impact on ecosystems depending on the change in CO₂ concentration accompanying the rise

(e.g., Good et al., 2011a). A high climate sensitivity and/or a higher proportion of non-CO₂ GHGs would imply a relatively low CO₂ rise at 2°C global warming, so the offsetting effects of CO₂ fertilization and increased water use efficiency would be smaller than for low climate sensitivity and/or a lower proportion of non-CO₂ GHGs.

4.2.4.5. Diffuse and Direct Radiation

The quantity and size distribution of aerosols in the atmosphere alters both the amount of solar radiation reaching the Earth's surface and the proportions of direct versus diffuse radiation. In some regions, direct radiation has been reduced by up to 30 W m⁻² over the industrial era, with an accompanying increase in diffuse radiation of up to 20 W m⁻² (Kvalevåg and Myhre, 2007). The global mean direct and diffuse radiation changes due to aerosols are -3.3 and +0.9 W m⁻², respectively (Kvalevåg and Myhre, 2007). For a constant total radiation, an increased fraction received as diffuse radiation theoretically increases net photosynthesis because a smaller fraction of the vegetation canopy is light-saturated, making photosynthesis more light efficient at the canopy scale (Knohl and Baldocchi, 2008; Kanniah et al., 2012). In a global model that included this effect, an increase in diffuse fraction of solar radiation due to volcanic and anthropogenic aerosols and cloud cover was simulated to lead to approximately a 25% increase in the strength of the global land carbon sink between 1960 and 1999; however, under a scenario of climate change and decreased anthropogenic aerosol concentration, this enhancement declined to near zero by the end of the 21st century (Mercado et al., 2009). All RCPs project decreased aerosol concentrations due to air quality protection measures, as already seen in some countries. The influence of the form of radiation on plant growth and the land carbon budget is a potentially important unintended consequence of solar radiation management schemes that involve the injection of aerosols into the stratosphere to reduce radiant forcing (see WGI AR5 Section 7.7), but this topic is at present insufficiently researched for adequate assessment.

4.2.4.6. Invasive and Alien Species

Since the IPCC AR4, the number of observations of the spread and establishment of alien species attributed to climate change has increased for several taxa (e.g., Walther et al., 2009) and for particular areas, including mountain tops and polar regions (McDougall et al., 2011; Chown et al., 2012). Species invasions have increased over the last several decades (*very high confidence*), and the aggressive expansion of plant and animal species beyond their historical range is having increasingly negative impacts on ecosystem services and biodiversity (*high confidence*; Brook, 2008; Burton et al., 2010; McGeoch et al., 2010; Simberloff et al., 2013). Climate change will exacerbate some invasion impacts and ameliorate others (Peterson et al., 2008; Bradley et al., 2009; Britton et al., 2010; Bellard et al., 2013). Although there is increasing evidence that some species invasions have been assisted by climate change, there is *low confidence* that species invasions have in general been assisted by recent climatic trends because of the overwhelming importance of human-facilitated dispersal in mediating invasions. The spread of alien species has several causes, including habitats made favorable by climate change (Walther et al., 2009), deliberate species

Frequently Asked Questions

FAQ 4.3 | Will the number of invasive alien species increase as a result of climate change?

Some invasive plants and insects have already been shown to benefit from climate change and will establish and spread into new regions (where they are “aliens”), once they are introduced. The number of newly arrived species and the abundance of some already established alien species will increase because climate change will improve conditions for them. At the same time, increasing movement of people and goods in the modern world, combined with land use changes worldwide, increases the likelihood that alien species are accidentally transported to new locations and become established there. There are many actions that can be taken to reduce, but not eliminate, the risk of alien species invasions, such as the treatment of ballast water in cargo ships and wood products, strict quarantine applied to crop and horticultural products, and embargos on the trade and deliberate introduction of known invader species. Some invasive species will suffer from climate change and are expected to decrease in range and population size in some regions. Generally, increased establishment success and spread will be most visible for those alien species that have characteristics favored by the changing climate, such as those that are drought tolerant or able to take advantage of higher temperatures.

transfer, and accidental transfer due to increased global movement of goods.

In most cases climate change increases the likelihood of the establishment, growth, spread, and survival of invasive species populations (Dukes et al., 2009; Walther et al., 2009; Bradley et al., 2010; Huang et al., 2011; Chown et al., 2012). Some degree of climate/habitat match has been found to be a prerequisite of establishment success across seven major plant and animal groups (Hayes and Barry, 2008). A range of alien species responses and local consequences are expected (e.g., Rahel and Olden, 2008; Frelich et al., 2012; Haider et al., 2012; West et al., 2012). Invasive species, compared to native species, may have traits that favor their survival, reproduction, and adaptation under changing climates; invasive plants in particular tend to have faster growth rates and are particularly favored when resources are not limited (*medium to high confidence*; van Kleunen et al., 2010; Willis, C.G. et al., 2010; Buswell et al., 2011; Davidson et al., 2011; Zerebecki and Sorte, 2011; Haider et al., 2012; Matzek, 2012). Some invasive plants are more drought tolerant (Crous et al., 2012; Matzek, 2012; Perry et al., 2012), and on average they have higher overall metabolic rates, foliar nitrogen concentrations, and photosynthetic rates than their native counterparts (Leishman et al., 2007).

Extreme climate events provide opportunities for invasion by generating disturbances and redistributing available resources (Diez et al., 2012) and changing connectivity between different ecosystems. Current warming has already enabled many invasive alien species, including plant, vertebrate, invertebrate, and single-cell taxa, to extend their distributions into new areas (*high confidence* for plants and insects; Walther et al., 2009; Smith et al., 2012). However, population declines and range contractions are predicted for some invasive species in parts of their ranges (Bradley et al., 2009; Sobek-Swant et al., 2012; Taylor et al., 2012; Bertelsmeier et al., 2013). The expansion of invasive species in some areas and contraction in others will contribute to community reorganization and the formation of novel ecosystems and interactions in both terrestrial and freshwater habitats (*high confidence*; e.g., Britton et al., 2010; Kiesecker, 2011; Martinez, 2012; see also Section 4.3.2.5). For example, invasive grasses may be favored over native ones with increasing

temperatures (Parker-Allie et al., 2009; Chuine et al., 2012; Sandel and Dangremond, 2012).

In a few cases, benefits to biodiversity and society may result from the interactive effects of climate change and invasive species, such as increases in resources available to some threatened species (Caldow et al., 2007), forest structural recovery (Bolte and Degen, 2010), and available biomass for timber and fuel (van Wilgen and Richardson, 2012). The effect of invasions on net changes in carbon stocks are situation specific and may be either positive or negative (Williams, A.L. et al., 2007). Rising CO₂ levels will increase the growth rates of most invasive plant species (Mainka and Howard, 2010; but see Section 4.2.4.4). The effectiveness of invasive alien species management for sequestering carbon is uncertain and context specific (Peltzer et al., 2010). Longer term, indirect effects of invasive alien species will be more important than direct, short-term effects, for instance, as a result of changes in soil carbon stocks and tree community composition (*low to medium confidence*; Peltzer et al., 2010).

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

A range of climate change-related variables (extreme events and changes in precipitation, temperature, and CO₂) will continue to exacerbate the establishment and spread of pests, vectors, and pathogens and negatively impact production systems (*medium confidence*; Robinet and Roques, 2010; Clements and Ditommaso, 2011). Warming has contributed to the spread of many invasive insect species, such as the mountain pine

bark beetle, and resulted in forest destruction (*high confidence*; Raffa et al., 2008). The interactions between crop growth, climate change, and pest or pathogen dynamics are difficult to predict (West et al., 2012). Management strategies may become less effective as a consequence of the decoupling of biocontrol relationships and less effective mechanical control as biomass and/or population size of invasive species increases (*low to medium confidence*; Hellmann et al., 2008).

4.3. Vulnerability of Terrestrial and Freshwater Ecosystems to Climate Change

The vulnerability of ecosystems to climate change, that is, their propensity to be adversely affected, is determined by the sensitivity of ecosystem processes to the particular elements of climate undergoing change and the degree to which the system (including its coupled social elements) can maintain its structure, composition, and function in the presence of such change, either by tolerating or adapting to it. Tolerance and adaptability both interact with exposure, which in the case of terrestrial and freshwater ecosystems means the magnitude and rate of climate change relative to ranges of climatic conditions and rates of change under which the ecosystem developed and its organisms evolved. Chapter 19 provides a full discussion on vulnerability concepts.

4.3.1. Changes in the Disturbance Regime

The species composition at a given location is determined by three considerations: the ability of species to reach the location; the physiological tolerance of the species in relation to the range of conditions experienced there; and interactions with other species, including competitors, symbionts, predators, prey, and pathogens. Occasional disturbances relieve competition, create opportunities for the establishment and success of less dominant species, and may facilitate dispersal. Moderate disturbance is thus important in maintaining diversity and ecosystem function (Connell, 1978). Exposure to disturbances keeps tolerance of disturbance in the population high. Fire, floods, and strong winds are all examples of biodiversity-sustaining climate disturbances, provided that their frequency and intensity do not deviate greatly above or below the regime to which the species are adapted. Average environmental conditions may be less of a determinant of species range and abundance than the extreme conditions, such as the occurrence of exceptionally cold or hot days or droughts exceeding a certain duration (Zimmermann et al., 2009). The projected changes in probability of extremes are typically disproportionately larger than the projected changes in the mean (see IPCC, 2012; but also Diffenbaugh et al., 2005). Biotic disturbances, such as pest and pathogen outbreaks are also often implicated in ecosystem change, and may be enabled by climate change.

It is suggested that ecosystem regime shifts resulting from climate change (alone or in interaction with other factors) will often be triggered by changes in the disturbance regime, rather than by physiological tolerance for the mean conditions (Thonicke et al., 2001). A “disturbance regime” refers to the totality of different types of disturbance events in a system, each characterized by its probability of occurrence, intensity, and other relevant attributes, such as its seasonal pattern. A corollary is that disturbance-related change is abrupt rather than gradual. Change

in the fire disturbance regime is emerging as a key proximal mechanism and early indicator of terrestrial ecosystem change (Girardin et al., 2009; Johnstone et al., 2010). Changes in the fire regime have in some cases been attributed to climate change (Littell et al., 2009). Regional trends in fire occurrence have been observed since 2000 (Giglio et al., 2013), but interpreting their significance requires a longer term perspective (e.g., Bergeron et al., 2010).

4.3.2. Observed and Projected Change in Ecosystems

This section highlights key observed changes in terrestrial and freshwater ecosystems over the recent past, as well as changes projected during the 21st century. For observations, we assess the degree of confidence that change has been detected, and separately the confidence we have in attributing the change to climate change (Figure 4-4). Confidence in detection 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 Chapter 18; Mastrandrea et al., 2010). Note that a slightly different definition of detection is used here than in Chapter 18, 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 tests are satisfied: changes correspond to a sound mechanistic understanding of responses to climate change; the time series of observations is sufficiently long to detect trends correlated with climate change; and confounding factors can be accounted for or are of limited importance. In the sections that provide the details of the assessment of detection and attribution, estimated levels of confidence are given 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. In all cases the estimates of confidence levels are based on global and cross-taxon assessments, so the positioning may be different for specific taxa or regions. Some of the sections include assessments of model-based projections of future change; the confidence assessment of detection and attribution does not extend to these.

A key message arising from the analysis of *detection* and *attribution* is that climate impacts on the functioning of organisms and ecosystems are clearest when temperature is a principal driver, changes are relatively rapid, and confounding factors play a small role. At one end of the spectrum, the large warming signal over the last several decades in much of the Arctic tundra combined with minimal human impacts is associated with *high confidence* in detection of an increase in shrubs and permafrost thawing and *high confidence* in the attribution to climate warming (Section 4.3.3.1.1). Likewise, the phenology of most organisms is sensitive to temperature, confounding effects are often small, and the response is rapid, leading to *high confidence* in detection and attribution of changes in phenology to warming (Section 4.3.2.1). At the opposite end of the spectrum, species extinctions are very difficult to attribute to climate change (Section 4.3.2.5), in part because other factors dominate recent extinctions. This does not mean that climate has not played an important contributing role; indeed it has been argued that the low level of confidence in attribution is due to the lack of studies looking for climate signals in extinctions (Cahill et al., 2013). Similarly there is

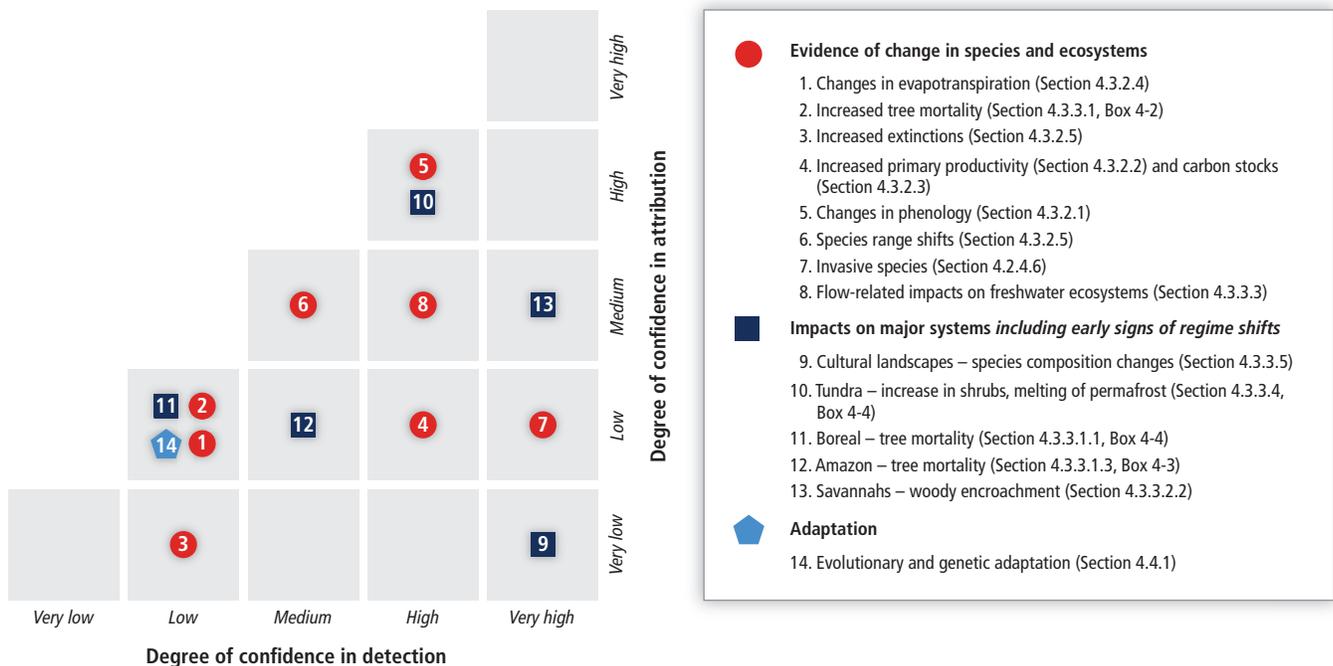


Figure 4-4 | Confidence in detection of change and attribution of observed responses of terrestrial ecosystems to climate change. Confidence levels are based on expert judgment of the available literature following the IPCC uncertainty guidance (Mastrandrea et al., 2010), attribution criteria outlined in Chapter 18, and detection criteria defined in the text. The symbols in the figure represent global and cross-taxa assessments; the positioning may be different for specific taxa or regions. Details of the assessments that were used in positioning each of the points can be found in the sections given in parentheses.

very good evidence that species composition is changing in cultural landscapes, but the important role of other factors, for example, land management and nitrogen deposition, makes attribution of a contribution to recent warming difficult. This analysis indicates that responses in most species and ecosystem levels will become more apparent over time because (1) observed organism-level changes will have long-term impacts on ecosystem functioning (*high confidence*; Sections 4.3.2.1, 4.3.2.5, 4.3.3) and (2) warming signals can be detected in ecosystems where the recent warming has been strong and confounding factors are minimal. In addition, the absence of observed changes does not preclude confident projections of future change for three reasons: climate change projected for the 21st century substantially exceeds the changes experienced over the past century in medium to high scenarios (all but RCP2.6); ecosystem responses to climate change may be nonlinear; and change may be apparent only after considerable time lags (Jones et al., 2009).

4.3.2.1. Phenology

Further evidence from ground-based and satellite studies, focused mainly on the NH (Northern Hemisphere), supports the AR4 conclusion that shifts in phenology have occurred over recent decades. “Spring advancement”—earlier occurrence of spring events, such as breeding, bud burst, breaking hibernation, flowering, migration—is seen in hundreds of plant and animal species in many regions (Menzel et al., 2006; Cleland et al., 2007; Parmesan, 2007; Primack et al., 2009; Cook et al., 2012a; Peñuelas et al., 2013), although magnitudes of change vary considerably and some species show no change (Parmesan, 2007).

Apparent discrepancies between two estimates of overall NH spring advancement noted in AR4 (-2.3 days per decade, Parmesan and Yohe, 2003; -5.1 days per decade, Root et al., 2003) are largely resolved when methodological differences are accounted for, particularly the inclusion of species that do not show phenological changes (Parmesan, 2007). A combined analysis of 203 species suggests NH spring advancement of -2.8 ± 0.35 days per decade (Parmesan, 2007).

4.3.2.1.1. Plants

Spring advancement is seen across the NH including North America (e.g., Cook et al., 2008, 2012b), Europe (e.g., Menzel et al., 2006; Cook et al., 2012b), Asia (e.g., Primack et al., 2009; Ma and Zhou, 2012), and the High Arctic (Høye et al., 2007). Changes are generally larger at higher latitudes. A meta-analysis indicates mean NH spring advancement of -1.1 ± 0.16 days per decade for herbs and grasses (85 species), -1.1 ± 0.68 days per decade for shrubs (6 species), and -3.3 ± 0.87 days per decade for trees (16 species), over a record period of 35 to 132 years, depending on the study. The warming trends detected in the well-mixed surface waters (epilimnion) of many lakes in North America, Eurasia, and Africa (Adrian et al., 2009) are associated with the earlier onset of spring phytoplankton blooms (Winder and Schindler, 2004; Winder and Sommer, 2012). Satellite data also indicate a general tendency of spring advancement, though there is variation between satellite studies, especially at local scales, due to the use of different instruments and methods (e.g., White et al., 2009). A study using the Advanced Very High Resolution Radiometer (AVHRR) suggests that for vegetation between 30°N and 80°N, the start of the growing season advanced by -5.2 days

between 1999 and 1982 and advanced a further -0.2 days by 2008; while the growing season end was delayed by 6.6 days between 1982 and 2008 (Jeong et al., 2011). Studies with a more recent satellite instrument, the Moderate Resolution Imaging Spectrometer (MODIS), also show spring advancement (e.g., Ahl et al., 2006). The relatively short duration of satellite observations makes trend detection particularly sensitive to the choice of analysis period.

4.3.2.1.2. Animals

Many new studies provide further evidence of changes in animal phenology (e.g., amphibians: Kusano and Inoue, 2008; Phillimore et al., 2010; birds: Pulido, 2007; Thorup et al., 2007; mammals: Adamik and Kral, 2008; Lane et al., 2012; insects: Robinet and Roques, 2010; freshwater plankton: Adrian et al., 2009). Changes in breeding phenology are reported from various regions and different taxa (e.g., Parmesan, 2006, 2007; Post et al., 2008; Primack et al., 2009). In the NH several studies show advancements of egg laying dates in birds (e.g., Parmesan, 2007: -3.7 ± 0.7 days per decade, in 41 species). In contrast, a delay of the mean breeding date by 2.8 to 3.7 days between 1950 and 2004 was seen for two of nine seabirds in the Eastern Antarctic, linked to decreased sea ice extent (Barbraud and Weimerskirch, 2006). Spring arrival dates have advanced for many migratory birds (e.g., Thorup et al., 2007). Patterns of changes in autumn migration in birds are mostly not consistent (delayed, advanced, no change) across analyzed species and regions and appear to be highly related to non-climatic variables (e.g., Sokolov, 2006; Adamik and Pietruszkova, 2008).

A large body of evidence therefore shows that, in NH temperate, boreal, and Arctic regions, spring advancement has occurred in many plant and animal species over the last several decades (*high confidence* due to *robust evidence* but only *medium agreement* when examined across all species and regions; Figure 4-4).

Understanding of the drivers of phenological change has also improved further since AR4. Many observational studies find a correlation with higher temperatures (Cook et al., 2012a). Experimental manipulation generally supports this (e.g., plants: Cleland et al., 2012; bird egg-laying: Visser et al., 2009; insects: Musolin et al., 2010; Kollberg et al., 2013). Some individual studies find good agreement between experimental warming and *in situ* observations (e.g., Gunderson et al., 2012) although a meta-analysis suggests that experiments can substantially under-predict advances in the timing of flowering and leafing of plants in comparison with observational studies (Wolkovich et al., 2012). Observational data can also be affected by methodological issues; for example, flipper-tagging of penguins can alter their migratory behavior (Saraux et al., 2011). Rates of warming across a season may also be important (Schaper et al., 2012). Models can be used to explain relationships between observed phenological changes and environmental variables. For example, a model based on water temperature captured the observed temporal and spatial variation in *Daphnia* phenology in NH lakes (Straile et al., 2012). Other environmental factors related to temperature, such as timing of snowmelt, snow cover, and snow depth, can play a role. Snowmelt changes led to earlier flowering and appearances of plants and arthropods in Greenland between 1996 and 2005 (Høye et al., 2007) and earlier flowering in an alpine plant in the Rocky Mountains,

USA, between 1975 and 2008 (Hülber et al., 2010; Lambert et al., 2010). Earlier snowmelts decreased floral resources and hence affected insect population dynamics in mountain ranges in the USA in the years 1980, 1985, 1986, and 1989 (Boggs and Inouye, 2012). In Colorado, USA, the yellow-bellied marmot emerged earlier from hibernation due to snowmelts becoming earlier over 1976–2008 (Ozgul et al., 2010) while in Alberta, Canada, Columbian ground squirrels emerged later over 1992–2012 owing to delayed snowmelts associated with increased late-season snowstorms (Lane et al., 2012). Delayed emergence from hibernation was associated with decreased population growth rate (Lane et al., 2012). Food availability can be important; for example, in the Yukon area, Canada, the date of giving birth in North American squirrels (*Tamiascurus hudsonicus*) advanced by an average of -18 days over the period 1989–1998, coinciding with increasing abundance of white spruce cones, their major food source (Réale et al., 2003).

Phenological response can differ with migration strategy in birds, for example short-distance migrants show greater advancements in spring arrivals than long distant migrants (e.g., Saino et al., 2009; but see Parmesan, 2006 for different patterns). In a temperate region (Massachusetts, USA), declining sizes of populations and migrating cohorts of North American Passerine birds account for a large part of the variation in migration times between 1970 and 2002 (Miller-Rushing et al., 2008). The remaining variation was explained by climatic variables, migration distance, and date. The variation in bird migration phenology change can also be related to differing patterns of feather changes during moulting times, food availability at stop-over places, and differing health conditions of individual species (Gordo, 2007).

Although a number of non-climatic influences on phenology are also identified, an increased number of observational and experimental studies, across many organism types, suggest that warming has contributed to the overall spring advancement observed in the NH (*high confidence* due to *high agreement* and *medium evidence*).

4.3.2.2. Primary Productivity

Primary production, the process of plant growth, is fundamental to the global carbon cycle (see Section 4.3.2.3) and underpins provisioning ecosystem services such as food, timber, and grazing. 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 sensitive to most aspects of climate change, is indirectly affected via the effects of climate on pests and diseases, and is responsive to many of the other changes simultaneously taking place in the world, such as described in Section 4.2.4. The diverse and frequently nonlinear form of responses to the factors influencing primary production, combined with the complexity of interactions between them, means that at a given location the net outcome can be an increase, no change, or a decrease in productivity.

The concentration of CO₂ in the atmosphere shows clear patterns in space and time largely related to the primary productivity of the land and oceans. The contribution by terrestrial ecosystems to these patterns can be estimated using isotope measurements, emission databases, and

models (Canadell et al., 2007). It consists of a sink term, due to increased net ecosystem production, plus a source term due to land use change. During the decade 2000–2009, land net primary productivity at the global scale continued to be enhanced about 5% relative to the estimated preindustrial level, leading to a land sink of $2.6 + 1.2 \text{ PgC yr}^{-1}$ (these values are from WGI AR5 Section 6.3.2.6; the uncertainty range is 2 standard deviations; for the primary literature see also Raupach et al., 2008; Le Quéré et al., 2009). The net uptake of carbon by the land is highly variable year to year, mainly in response to climate variation and major volcanic eruptions (Peylin et al., 2005; Sitch et al., 2008; Mercado et al., 2009). Given the uncertainty range, it is not possible to conclude whether the rate of carbon uptake by the residual land sink has increased or decreased over the past 2 decades (Raupach et al., 2008; WGI AR5 Section 6.3.2.6). Coupled Model Intercomparison Project Phase 5 (CMIP5) model projections, using the RCP scenarios, suggest that the rate of net carbon uptake by terrestrial ecosystems will decrease during the 21st century except under the RCP4.5 scenario, and by the greatest amount under RCP8.5. There is greater uncertainty between models than between scenarios; in some models terrestrial ecosystems become a net source of CO_2 to the atmosphere (WGI AR5 Section 6.4.3.2, especially Figure 6.26).

It is possible to downscale the land sink estimate continentally, using inversion modeling techniques and the growing network of precision atmospheric observations. There is *high agreement* and *medium evidence* that the net land uptake in natural and semi-natural terrestrial ecosystems is broadly distributed around the world, 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).

The observed trends in Normalized Difference Vegetation Index (NDVI), a satellite proxy for primary productivity, are discussed under various ecosystem-specific discussions above and 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, or simply reflect inadequacies in the indicator, method of analysis, and length of the record in relation to the high interannual variability. 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 subsequent observations show a lower rate and no geographical uniformity (Goetz et al., 2007). More than 25% of high-latitude 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 (Goetz et al., 2007). NDVI trend analyses in rangelands show varying patterns around the world, with substantial disagreement between studies (Millennium Ecosystem Assessment, 2005a; Bai et al., 2008; Beck, H.E. et al., 2011; 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 herbs; and to what degree it reveals land management efforts or responses to climate (Anyamba and Tucker, 2005; Prince et al., 2007; Hellden and Tottrup, 2008; Seaquist et al., 2009). In the period 2000–2009 no NDVI trend was apparent in the Sahel (Samanta et al., 2011).

Tree rings record changes in tree growth over approximately the past millennium. Many tree ring records show accelerated tree growth during much of the 20th century (Briffa et al., 2008), which often correlates with rising temperature. Variations in tree ring width, density, and isotopic composition arise from many factors, including temperature, moisture stress, CO_2 fertilization, N deposition, and O_3 damage, but also stand structure and management. Direct CO_2 effects, inferred from the ring record once the effects of drought and temperature have been accounted for, have been proposed for approximately 20% of the sites in the International Tree Ring Data Base (Gedalof and Berg, 2010) and studied in detail at some sites (Koutavas, 2008). Since the 1980s, a number of tree ring records show a decline in tree growth (Wilson et al., 2007). Several possible causes have been suggested for this, including increasing water stress and O_3 damage; but the most recent rings in most published tree ring chronologies date from before the 1990s (Gedalof and Berg, 2010), so tree ring-based conclusions for the past 2 decades are based on a relatively small body of evidence and may therefore be biased. Recent tree ring studies were often specifically designed to examine growth in response to environmental changes (Gedalof and Berg, 2010) and may therefore not be representative of global tree growth. Direct repeated measurements of tree girth increment in forest monitoring plots (discussed in Section 4.3.2.3) are an alternate data source for recent decades.

Primary production in freshwater lakes has been observed to increase in some Arctic (Michelutti et al., 2005) and boreal lakes, but to decrease in Lake Tanganyika in the tropics (O’Reilly et al., 2003). In both cases the changes were attributed by the authors to climate change.

In summary, there is *high confidence* that net terrestrial ecosystem productivity at the global scale has increased relative to the preindustrial era. There is *low confidence* in attribution of these trends to climate change. Most studies speculate that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis, but there is no clear, consistent signal of a climate change contribution (Figure 4-4).

4.3.2.3. Biomass and Carbon Stocks

The forest biomass carbon stock can be estimated from the routine forest monitoring that takes place for management and research purposes. Forest inventories were generally designed to track timber volumes; inferring total biomass and ecosystem carbon stocks requires further information and assumptions, which make absolute values less certain, but have a lesser effect on trend detection. Forest inventory systems are well developed for NH temperate and boreal forest (Nabuurs et al., 2010; Ryan et al., 2010; Wang, B. et al., 2010). Data for tropical and Southern Hemisphere forests and woodlands also exist (Maniatis et al., 2011; Tomppo et al., 2010) but are typically less available and comprehensive (Romijn et al., 2012). More and better data may become available as a result of advances in remote sensing (e.g., Baccini et al., 2012) and increased investment in forest monitoring through initiatives such as the Reduced Emissions from Deforestation and Degradation (REDD) of the United Nations Framework Convention on Climate Change (UNFCCC).

Forests have increased in biomass and carbon stocks over the past half century in Europe (Ciais et al., 2008; Luysaert et al., 2010) and the USA

(Birdsey et al., 2006). Canadian managed forests increased in biomass only slightly during 1998–2008, because growth was offset by significant losses due to fires and beetle outbreaks (Stinson et al., 2011). Several dozen sites across the moist tropics have been monitored to estimate forest biomass changes. In the Amazon (Phillips et al., 2009) forest biomass has generally increased in recent decades, dropping temporarily after a drought in 2005. Globally, for the period 2000–2007, recently undisturbed forests are estimated to have withdrawn 2.30 ± 0.49 PgC yr⁻¹ from the atmosphere, while formerly cleared tropical forests, now regrowing, withdrew an additional 1.72 ± 0.54 PgC yr⁻¹ (Pan et al., 2011). The global terrestrial carbon sink is partly offset by the losses of forest carbon stocks to the atmosphere through land use change, largely in the tropics, of 1.1 ± 0.8 PgC yr⁻¹ (2000–2009, WGI AR5 Section 6.3.2.6).

The carbon stock in global soils, including litter and peatlands is 1500 to 2400 PgC, with permanently frozen soils adding another 1700 PgC (Davidson and Janssens, 2006). The soil carbon stock is thus more than 10 times greater than the carbon stock in forest biomass (Kindermann et al., 2008). Changes in the size of the soil carbon stock result from changes in the net balance of inputs and losses over a period of many years. Inputs derive from primary production, discussed in Section 4.3.2.2, and are mostly modestly increasing under climate change. Losses result principally through the respiration of soil microbes, which increases with increasing temperature. The present and future temperature sensitivity of microbial respiration remains uncertain (Davidson and Janssens, 2006). An analysis of long-term respiration measurements from the soil around the world suggests that it has increased over the past 2 decades by an amount of 0.1 PgC yr⁻¹, some of which may be due to increased productivity (Bond-Lamberty and Thomson, 2010). If soil respiration were to exceed terrestrial net primary production globally and on a sustained basis, the present net terrestrial sink would become a net source, accelerating the rate of CO₂ build-up in the atmosphere (Luo, 2007).

The carbon stock in freshwater systems is also quite high in global terms. Annual rates of storage (0.03 to 0.07 PgC yr⁻¹) may be trivial compared with sequestration by soils and terrestrial vegetation, but lake sediments are preserved over longer time scales (+10 kyr compared with decades to centuries), and Holocene storage of carbon in lake sediments has been estimated at 820 Pg (Cole et al., 2007). Manmade impoundments represent an increasing and short-lived additional carbon store with conservative annual estimates of 0.16 to 0.2 PgC yr⁻¹ (Cole et al., 2007).

A short-duration study of the temperature sensitivity of decomposition in flooded coastal soils, extrapolated to the 21st century, suggested that increases in respiration would exceed increases in future production (Kirwan and Blum, 2011). Further detail on wetland soil carbon stocks can be found in Section 4.3.3.3 on peatlands and on permafrost carbon stocks in Box 4-4 and in Chapter 28.

In summary, biomass and soil carbon stocks in terrestrial ecosystems are currently increasing (*high confidence*) but are vulnerable to loss to the atmosphere as a result of rising temperature, drought, and fire projected in the 21st century (Figure 4-4). 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*).

4.3.2.4. Evapotranspiration and Water Use Efficiency

Evapotranspiration (ET) includes evaporation from the ground and vegetation surfaces, and transpiration through plant stomata. Both are affected by multiple factors (Luo et al., 2008) including temperature, solar (shortwave) and thermal (longwave) radiation, humidity, soil moisture, and terrestrial water storage; transpiration is additionally affected by CO₂ concentration through its influence on plant stomatal conductance. Studies using lysimeters, evaporation pans, the balance of observed precipitation and runoff, and model reconstructions indicate both increases and decreases in ET in different regions and between approximately 1950 and the present (Huntington, 2008; Teuling et al., 2009; Douville et al., 2013). Flux tower records have at most 15 years duration (FLUXNET, 2012), so there are insufficient data to calculate large-scale, long-term trends. ET can also be estimated from meteorological observations or simulated with models constrained by observations. Estimates of ET from 1120 globally (but non-uniformly) distributed stations indicate that global land mean ET increased by approximately 2.2% between 1982 and 2002, a rate of increase of 0.75 mm yr⁻² (Wang, K. et al., 2010). Other studies, using data-constrained models, indicated global ET rises of between 0.25 and 1.1 mm yr⁻² during the 1980s and 1990s (Jung et al., 2010; Vinukollu et al., 2011; Zeng et al., 2012), possibly linked with increased surface solar radiation and thermal radiation (Wild et al., 2008) or warming (Jung et al., 2010). There has been no significant ET trend since approximately 2000 (Jung et al., 2010; Vinukollu et al., 2011; Zeng et al., 2012), possibly due to soil moisture limitation (Jung et al., 2010). Overall, there is *low confidence* in both detection and attribution of long-term trends in ET (Figure 4-4).

Experiments show that rising CO₂ decreases transpiration and increases intrinsic water use efficiency (iWUE, the ratio of photosynthesis to stomatal conductance; Leakey et al., 2009). Some modeling studies suggest that, over the 20th century, the effects of CO₂ on decreasing transpiration are of comparable size but opposite to the effects of rising temperature (Gerten et al., 2008; Peng et al., 2013). However, the observed general increase in ET argues that reduced transpiration cannot be the dominant factor (Huntington, 2008). A meta-analysis of studies at 47 sites across five ecosystem types (Peñuelas et al., 2011) suggests that iWUE for mature trees increased by 20.5% between the 1970s and 2000s. Increased iWUE since preindustrial times (1850 or before) has also been found at several forest sites (Andreu-Hayles et al., 2011; Gagen et al., 2011; Loader et al., 2011; Nock et al., 2011) and also in a temperate semi-natural grassland since 1857 (Koehler et al., 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen et al., 2011).

4.3.2.5. Changes in Species Range, Abundance, and Extinction

Species respond to climate change through genotypic adaptation and phenotypic plasticity; by moving out of unfavorable and into favorable climates; or by going locally or globally extinct (Dawson et al., 2011; Bellard et al., 2012; Peñuelas et al., 2013; see also Section 4.2.3). These responses to climate change can potentially have large impacts on biodiversity and ecosystem services. Genotypic adaptation in the face of strong selection pressure from climate change is typically accompanied

Frequently Asked Questions

FAQ 4.4 | How does climate change contribute to species extinction?

There is a consensus that climate change over the coming century will increase the risk of extinction for many species. When a species becomes extinct, a unique and irreplaceable life form is lost. Even local extinctions can impair the healthy functioning of ecosystems.

Under the fastest rates and largest amounts of projected climate change, many species will be unable to move fast enough to track suitable environments, which will greatly reduce their chances of survival. Under the lowest projected rates and amounts of climate change, and with the assistance of effective conservation actions, the large majority of species will be able to adapt to new climates, or move to places that improve their chances of survival. Loss of habitat and the presence of barriers to species movement increase the risk of extinctions as a result of climate change.

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 recent extinctions is the subject of considerable debate.

by large reductions in abundance (see Section 4.4.1.2). Species range shifts are accompanied by changes in abundance, local extinctions, and colonization that can alter ecosystem services when they affect dominant species such as trees, keystone species such as pollinators, or species that are vectors for diseases (Zarnetske et al., 2012). Global extinctions result in the permanent loss of unique forms of life.

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

4.3.2.5.1. Observed species range shifts

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

of species groups (i.e., broad taxonomic categories of species) and species within these groups to track changes in climate through range shifts (Angert et al., 2011; Mattila et al., 2011; Chen et al., 2011). For example, butterflies appear to be able track climate better than birds (community shifts: Devictor et al., 2012; but see Chen et al., 2011 for range shifts) while some plants appear to be lagging far behind climate trends except in mountainous areas (Bertrand et al., 2011; Doxford and Freckleton, 2012; Gottfried et al., 2012; Zhu et al., 2012; Telwala et al., 2013). There is growing evidence that responses at the “trailing edge” of species distributions (i.e., local extinction in areas where climate has become unfavorable) are often less pronounced than responses at the “leading edge” (i.e., colonization of areas where climate has become favorable), which may be related to differences in the rates of local extinction vs. colonization processes (Doak and Morris, 2010; Chen et al., 2011; Brommer et al., 2012; Sunday et al., 2012) and difficulties in detecting local extinction with confidence (Thomas et al., 2006).

Rising water temperatures are also implicated in species range shifts in river fish communities (e.g., Comte and Grenouillet, 2013), combined with a decrease in recruitment and survival as well as range contraction of cold-water species such as salmonids (Bartholow, 2005; Bryant, 2009; Ficke et al., 2007; Jonsson and Jonsson, 2009; Hague et al., 2011). Shifts in freshwater fish species range toward higher elevation and upstream (Hickling et al., 2006; Comte and Grenouillet, 2013) also are not keeping pace with the rate of warming in streams and rivers. While these changes in river temperature regimes may also open up new habitat at higher latitudes (or altitudes) for migratory (Reist et al., 2006) and cool- and warm-water species of fish (Tisseuil et al., 2012), there is *high confidence* that range contraction threatens the long-term persistence of some fully aquatic species.

Rates of recent climate change have varied greatly across the globe, ranging from rapid warming to cooling (Burrows et al., 2011; Dobrowski et al., 2013). Taking this spatial variation into account should enhance the ability to detect climate-related range shifts. A recent synthesis of range shifts indicates that terrestrial animal species have moved at rates that correspond better with changes in temperature when climate is measured only in the regions where the range shifts were observed

(Chen et al., 2011), providing greater confidence in attribution of the range shifts to climate change. Average range shifts across taxa and regions in this study were approximately 17 km poleward and 11 m up in altitude per decade, velocities that are two to three times greater than previous estimates (compare with Parmesan and Yohe, 2003; Fischlin et al., 2007), but these responses differ greatly among species groups. However, this approach remains a simplification, as the climate drivers of species range changes, for example, temperature and precipitation, have frequently shifted in different geographical directions (Dobrowski et al., 2013). Disentangling these conflicting climate signals can help explain complex responses of species ranges to changes in climate (Tingley et al., 2012). Overall, studies since AR4 show that species range changes result from interactions among climate drivers and between climate and non-climate factors. It is the greater understanding of these interactions, combined with increased geographical scope, that leads to *high confidence* that several well-studied species groups, such as insects and birds, have shifted their ranges over significant distances (tens of kilometers or more) over the last several decades, and that these range shifts can be attributed to changes in climate. But for many other species groups range shifts are more difficult to attribute to changes in climate because the climate signal is small, there are many confounding factors, differences between expected and observed range shifts are large, or variability within or between studies is high. Thus there is only *medium confidence* in detection and attribution when examined across all species and all regions.

4.3.2.5.2. Future range shifts

Projections of climate change impacts on future species range shifts since the AR4 have been dominated by studies using Ecological Niche Models (ENMs) that project future ranges based on correlative models of current relationships between environmental factors and species distribution (Peterson et al., 2011). A variety of process-based models are starting to be more widely used to make projections of future species distributions (Buckley et al., 2010; Beale and Lennon, 2012; Cheaib et al., 2012; Higgins et al., 2012; Foden et al., 2013). Model comparisons show that correlative models generally predict larger range shifts than process-based models for trees (Morin and Thuiller, 2009; Kearney et al., 2010; Cheaib et al., 2012). For other species groups that have been studied, differences in projections between model types show no clear tendency (Kearney et al., 2009; Buckley et al., 2010; Bateman et al., 2012). There has been some progress in model validation: projected species shifts are broadly coherent with species responses to climate change in the paleontological record and with observed recent species shifts (see Section 4.2.2 and above in this section), but further validation is needed (Green et al., 2008; Pearman et al., 2008; Nogues-Bravo et al., 2010; Dawson et al., 2011). Modeling studies typically do not account for a number of key mechanisms mediating range shifts, such as genetic adaptation and phenotypic plasticity (see Section 4.4.1.2), species interactions, or human-mediated effects. An important limitation in most studies is that realistic species displacement rates are not accounted for (i.e., rates at which species are able to shift their ranges through dispersal and establishment); as such, they only indicate changes in the location of favorable and unfavorable climates, from which potential shifts in species distribution can be inferred, but not rates of change (Bateman et al., 2013).

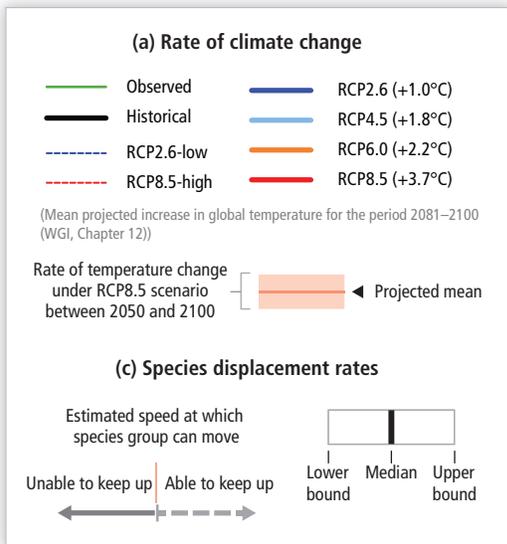
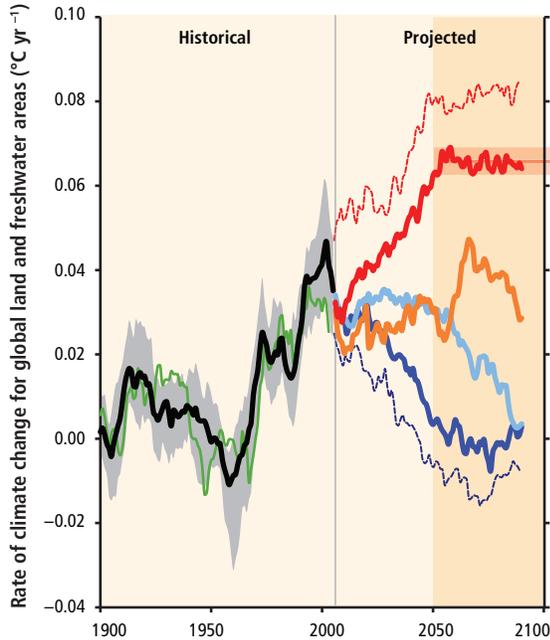
Analyses and models developed since AR4 permit the estimation of the ability of a wide range of species to track climate change. Figure 4-5 provides a synthesis of the projected abilities of several species groups to track climate change. This analysis is based on (1) past and future climate velocity, which is a measure of the rate of climate displacement across a landscape and provides an indication of the speed at which an organism would need to move in order to keep pace with the changing climatic conditions (Loarie et al., 2009; Burrows et al., 2011; Chen et al., 2011; Sandel et al., 2011; Feeley and Rehm, 2012; Dobrowski et al., 2013); and (2) species displacement rates across landscapes for a broad range of species (e.g., Stevens, V.M. et al., 2010; Nathan et al., 2011; Barbet-Massin et al., 2012; Kappes and Haase, 2012; Meier et al., 2012; Schloss et al., 2012; see additional references in Figure 4-5 legend). Comparisons of these rates indicate whether species are projected to be able to track climate as it changes. When species displacement capacity exceeds climate velocity it is inferred that species will be able to keep pace with climate change; when displacement capacity is lower than projected climate velocities then they will not, within the bounds of uncertainty of both parameters. This simplified analysis is coherent with more sophisticated model analyses of climate-induced species displacement across landscapes, some of which have evaluated additional constraints such as demographics, habitat fragmentation, or competition (e.g., Meier et al., 2012; Schloss et al., 2012).

Rates of climate change over the 20th century and projected for the 21st century are shown in Figure 4-5a. Rates of climate change for global land surfaces are given for IPCC AR5 climate projections under a wide range of GHG emissions scenarios (i.e., WGI AR5 Chapter 12; Knutti and Sedláček, 2012). Rates of global warming for land surfaces have averaged approximately $0.03^{\circ}\text{C yr}^{-1}$ since 1980, but have slowed over the last decade and a half (WGI AR5 Chapter 2). At the low end of projected future rates of warming, rates decrease over time, reaching near zero by the end of the century (RCP2.6). At the high end, projected rates increase over time, exceeding $0.06^{\circ}\text{C yr}^{-1}$ by the end of the century (RCP8.5), and perhaps above $0.08^{\circ}\text{C yr}^{-1}$ at the upper bound.

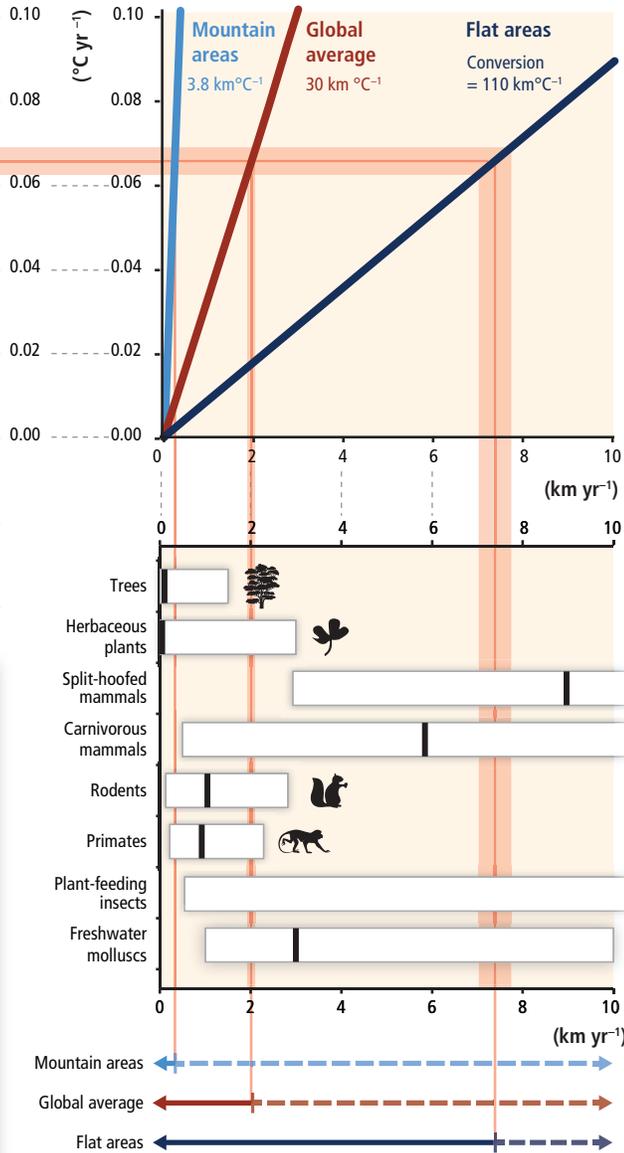
Climate velocity is defined as the rate of change in climate over time (e.g., $^{\circ}\text{C yr}^{-1}$, if only temperature is considered) divided by the rate of change in climate over distance (e.g., $^{\circ}\text{C km}^{-1}$, if only temperature is considered) and therefore depends on regional rates of climate change and the degree of altitudinal relief (Figure 4-5b; Loarie et al., 2009; Dobrowski et al., 2013). For example, climate velocity for temperature is low in mountainous areas because the change in temperature over short distances is large (e.g., Rocky Mountains, Andes, Alps, Himalayas; Figure 4-5b, leftmost axis). Climate velocity for temperature is generally high in flat areas because the rate of change in temperature over distance is low (e.g., parts of the USA Midwest, Amazon basin, West Africa, central Australia; Figure 4-5b, rightmost axis). In flat areas, climate velocity can exceed 8 km yr^{-1} for the highest rates of projected climate change (RCP8.5). We have focused on climate velocity for temperature change, but several analyses also account for precipitation change.

Rates of displacement vary greatly within and among species groups (Figure 4-5c). Some species groups, notably herbaceous plants and trees, generally have very low displacement capacity. Other species groups such as butterflies, birds (not shown), and large vertebrates generally have a very high capacity to disperse across landscapes, nonetheless

(a) Climate change scenarios



(b) Estimate of climate velocity to determine rate of displacement



(c) Species displacement rates (required to track climate velocity)

Figure 4-5 | (a) Rates of climate change, (b) corresponding climate velocities, and (c) rates of displacement of several terrestrial and freshwater species groups in the absence of human intervention. Horizontal and vertical pink bands illustrate the interpretation of this figure. Climate velocities for a given range of rates of climate change are determined by tracing a band from the range of rates in (a) to the points of intersection with the three climate velocity scalars in (b). Comparisons with species displacement rates are made by tracing vertical bands from the points of intersection on the climate velocity scalars down to the species displacement rates in (c). Species groups with displacement rates below the band are projected to be unable to track climate in the absence of human intervention. (a) Observed rates of climate change for global land areas are derived from Climatic Research Unit/Hadley Centre gridded land-surface air temperature version 4 (CRUTEM4) climate data reanalysis; all other rates are calculated based on the average of Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model ensembles for the historical period (gray shading indicates model uncertainty) and for the future based on the four Representative Concentration Pathway (RCP) emissions scenarios. Data were smoothed using a 20-year sliding window, and rates are means of between 17 and 30 models using one member per model. Global average temperatures at the end of the 21st century for the four RCP scenarios are from WGI AR5 Chapter 12. (b) Estimates of climate velocity for temperature were synthesized from historical and projected future relationships between rates of temperature change and climate velocity (historical: Burrows et al., 2011; Chen et al., 2011; Dobrowski et al., 2013; projected future: Loarie et al., 2009; Sandel et al., 2011; Feeley and Rehm, 2012). The three scalars are climate velocities that are representative of mountainous areas (left), averaged across global land areas (center), and large flat regions (right). (c) Rates of displacement are given with an estimate of the median (black bars) and range (boxes = approximately 95% of observations or models for herbaceous plants, trees, and plant-feeding insects or median \pm 1.5 inter-quartile range for mammals). Displacement rates for herbaceous plants were derived from paleobotanical records, modern plant invasion rates, and genetic analyses (Kinlan and Gaines, 2003). Displacement estimates for trees are based on reconstructed rates of tree migration during the Holocene (Clark, 1998; Clark et al., 2003; Kinlan and Gaines, 2003; McLachlan et al., 2005; Nathan, 2006; Pearson, 2006) and modeled tree dispersal and establishment in response to future climate change (Higgins et al., 2003; Iversen et al., 2004; Epstein et al., 2007; Goetz et al., 2011; Nathan et al., 2011; Meier et al., 2012; Sato and Ise, 2012). Displacement rates for mammals were based on modeled dispersal rates of a wide range of mammal species (mean of Schloss et al., 2012 for Western Hemisphere mammals and rates calculated from global assessments of dispersal distance by Santini et al., 2013 and generation length by Pacifici et al., 2013). Displacement rates for phytophagous insects are based on observed dispersal distances and genetic analyses (Peterson and Denno, 1998; Kinlan and Gaines, 2003; Schneider, 2003; Berg et al., 2010; Chen et al., 2011). The estimate of median displacement rate for this group exceeds the highest rates on the axis. These displacement rates do not take into account limitations imposed by host plants. Displacement estimates for freshwater molluscs correspond to the range of passive plus active dispersal rates for upstream movement (Kappes and Haase, 2012).

some species in these groups have low dispersal capacity. Current and future rates of climate change correspond to climate velocities that exceed rates of displacement for several species groups for most climate change scenarios. This is particularly true for mid- and late-successional trees that have maximum displacement rates that are on the order of tens to a few hundreds of meters per year. Overall, many plant species are foreseen to be able to track climates only in mountainous areas at medium to high rates of warming, though there is uncertainty concerning the potential role of long-distance dispersal (Pearson, 2006). Primates generally have substantially higher dispersal capacity than trees; however, a large fraction of primates are found in regions with very high climate velocities, in particular the Amazon basin, thereby putting them at high risk of being unable to track climates even at relatively low rates of climate change (Schloss et al., 2012). On a global average, many rodents, as well as some carnivores and freshwater molluscs, are projected to be unable to track climate at very high rates of climate change (i.e., $>0.06^{\circ}\text{C yr}^{-1}$). These projected differences in species ability to keep pace with future climate change are broadly coherent with observations of species ability or inability to track recent global warming (see Section 4.3.2.5.1).

Humans can increase species displacement rates by intentionally or unintentionally dispersing individuals or propagules. For example, many economically important tree species may be deliberately moved on large scales as part of climate adaptation strategies in forestry in some regions (Lindner et al., 2010). Human activities can also substantially reduce displacement rates. In particular, habitat loss and fragmentation typically reduces displacement rates, sometimes substantially (Eycott et al., 2012; Hodgson et al., 2012; Meier et al., 2012; Schloss et al., 2012). The degree to which habitat fragmentation slows displacement depends on many factors, including the spatial pattern of the fragments and corridors, maximum dispersal distances, population dynamics, and the suitability of intervening modified habitats as stepping-stones (Pearson and Dawson, 2003). Species and habitat dependencies may also speed or hinder species displacement. For example, host plants are projected to move much more slowly than most herbivorous insects, substantially slowing displacement of the insects if they are unable to switch host plants (Schweiger et al., 2012). Likewise, many habitats are structured by slow moving plants, so habitat shifts are projected to lag behind climate change (Hickler et al., 2012; Jones et al., 2012), which will in turn mediate the movements of habitat specialists.

There are significant uncertainties in climate velocities, measured estimates of dispersal and establishment rates, and model formulations. Climate velocities are calculated using a variety of methods and spatial resolutions, making direct comparisons difficult and leading to *low confidence* in estimates of climate velocities in Figure 4-5b (*limited evidence* and *medium agreement*). The lowest estimates of global average climate velocity (Figure 4-5b, center axis) are about half the best estimate values we show on the climate velocity axes (Loarie et al., 2009), while the highest estimates are about four times higher (Burrows et al., 2011), but high estimates may be artefacts of using very large spatial resolutions (Dobrowski et al., 2013). In addition, the climate velocities used in Figure 4-5 are based on temperature alone, and recent analyses indicate that including more climate factors increases climate velocity (Feeley and Rehm, 2012; Dobrowski et al., 2013). Species displacement rates are calculated based on a very wide range of methods including rates of

displacement in the paleontological record, rates of current range shifts due to climate warming, models of dispersal and establishment, maximum observed dispersal distances and genetic analyses (e.g., Kinlan and Gaines, 2003; Stevens, V.M. et al., 2010). There are often large differences in estimates of dispersal rates across methods due to intrinsic uncertainties in the methods and differences in the mechanisms included (Kinlan and Gaines, 2003; Stevens, V.M. et al., 2010). For example, estimates of tree displacement rates are frequently based on models or observations that explicitly or implicitly include both dispersal of seeds and biotic and abiotic factors controlling establishment of adult trees. Displacement rates of trees are often more strongly limited by establishment than dispersal (Higgins et al., 2003; Meier et al., 2012). It is reasonable to expect that limits on establishment could also be important for other species groups, but often only dispersal rates have been calculated, leading to an overestimation of displacement rates. For trees there is *medium confidence* in projections of their displacement rates due to the large number of studies of past, current, and future displacement rates (*robust evidence* and *medium agreement*). Less is known for other broad species groups such as mammals, so there is only *low confidence* in estimates of their displacement capacity. Estimates for other groups, such as freshwater molluscs, are based on very little data, so estimates of their dispersal capacity are poorly constrained.

Despite large uncertainties in displacement capacity and climate velocity, the rates of displacement required to track the highest rates of climate change (RCP8.5) are so high that many species will be unable to do so (*high confidence*). Moderate rates of projected climate change (RCP4.5 and RCP6.0) would allow more species to track climate, but would still exceed the capacity of many species to track climate (*medium confidence*). The lowest rates of projected climate change (RCP2.6) would allow most species to track climate toward the end of the century (*high confidence*). This analysis highlights the importance of rates of climate change as an important component of climate change impacts on species and ecosystems. For example, differences in the magnitude of climate change between scenarios are small at mid-21st century (WGI AR5 Chapter 12), but the differences in rates of climate change are large. At mid-century, it is projected that species would need to move little at the lowest rates of climate change (RCP2.6), but will need to move approximately 70 km per decade in flat areas in order to track climate at the highest rates of climate change (RCP8.5).

Species that cannot move fast enough to keep pace with the rate of climate change will lose favorable climate space and experience large range contractions (Warren et al., 2013), whereas displacement that keeps pace with climate change greatly increases the fraction of species that can maintain or increase their range size (Menéndez et al., 2008; Pateman et al., 2012). Mountains provide an extremely important climate refuge for many species because the rate of displacement required to track climate is low (Figure 4-5b; Colwell et al., 2008; Engler et al., 2011; Gottfried et al., 2012; Pauli et al., 2012; but see Dullinger et al., 2012). However, species that already occur near mountaintops (or other boundaries) are among the most threatened by climate change because they cannot move upwards (Ponniah and Hughes, 2004; Thuiller et al., 2005; Raxworthy et al., 2008; Engler et al., 2011; Sauer et al., 2011). The consequences of losing favorable climate space are not yet well understood. The extent to which adaptive responses might allow persistence in areas of unfavorable climates is discussed in Section

4.4.1.2. In the absence of adaptation, losing favorable climate space is projected to lead to reduced fitness, declining abundance, and local extinction, with potentially large effects on biodiversity and ecosystem services (see evidence of early signs of this for trees in Box 4-2).

4.3.2.5.3. Observed changes in abundance and local extinctions

Observations of range shifts imply changes in abundance, that is, colonization at the “leading edge” and local extinction at the “trailing edge” of ranges. Evidence that the attribution of these responses to recent changes in climate can be made with *high confidence* for several species groups is reviewed here (Section 4.3.2.5), in AR4, and by Cahill et al. (2013). Changes in abundance, as measured by changes in the population size of individual species or shifts in community structure within existing range limits, have also occurred in response to recent global warming (*high confidence*; Thaxter et al., 2010; Bertrand et al., 2011; Naito and Cairns, 2011; Rubidge et al., 2011; Devictor et al., 2012; Tingley et al., 2012; Vadadi-Fulop et al., 2012; Cahill et al., 2013; Ruiz-Labourdette et al., 2013). Confident attribution to recent global warming is hindered by confounding factors such as disease, land use change, and invasive species (Cahill et al., 2013). New tentative conclusions since AR4 are that climate-related changes in abundance and local extinctions appear to be more strongly related to species interactions than to physiological tolerance limits (*low confidence*; Cahill et al., 2013) and that precipitation can be a stronger driver of abundance change than temperature in many cases (Tian et al., 2011; Tingley et al., 2012). This gives weight to concerns that biological interactions, which are poorly known and modeled, may play a critical role in mediating the impacts of future climate change on species abundance and local extinctions (Dunn et al., 2009; Bellard et al., 2012; Hannah, 2012; Urban et al., 2012; Vadadi-Fulop et al., 2012).

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

Mountains also provide good examples of changes in abundance that can be linked to climate because very strong climate gradients are found there. AR4 highlighted these responses, and the case for changes in abundance, in particular plants, has become stronger since then. For

example, Pauli et al. (2012) reported an increase in species richness from plant communities of mountaintops in the European boreal and temperate zones due to increasing temperatures and a decrease in species richness on the Mediterranean mountain tops, probably due to a decrease in the water availability in southern Europe. An increase in the population size of warm-adapted species at high altitudes also appears to be attributable to increasing temperatures (Gottfried et al., 2012). However, these attributions are complicated by other anthropogenic influences such as changes in grazing pressure, atmospheric N deposition, and forest management practices (Gottfried et al., 2012). Altitudinal gradients in local and global extinctions of amphibians also contributed to the attribution of these extinctions to recent global warming, although this attribution remains controversial (see Section 4.3.2.5.5).

4.3.2.5.4. Projected changes in abundance and local extinction

Ecological niche models do not predict population changes, but the shifts in suitable climates can be used to infer areas where species populations might decline or increase. These models project that local extinction risk by the end of the 21st century due to climate change will vary widely, ranging from almost no increase in local extinction risk within the current range for some species or species groups to greatly increased risk of local extinctions in more than 95% of the present-day range for others (Settele et al., 2008; Bellard et al., 2012). Projected local colonization rates are equally variable. There has been progress in coupling species distribution models and species abundance models for a wide range of organisms (Keith et al., 2008; Midgley et al., 2010; Matthews et al., 2011; Schippers et al., 2011; Oliver et al., 2012a; Renwick et al., 2012). These hybrid approaches predict extinction risk directly, rather than by inference from changes in climate suitability (Fordham et al., 2012). The main conclusions from these studies are that changes in species abundance and local extinction risk as a result of climate change can range from highly positive to highly negative, and are determined by a combination of factors, including its environmental niche, demographics, and life history traits, as well as interactions among these factors (Aiello-Lammens et al., 2011; Clavero et al., 2011; Conlisk et al., 2012; Fordham et al., 2012; Swab et al., 2012).

Changes in abundances will also be accompanied by changes in genetic diversity (see also Section 4.4.1.2). At the intraspecific level, future climate change is projected to induce losses of genetic diversity when it results in range contraction (Balint et al., 2011; Pauls et al., 2013). In addition, there is theoretical and observational evidence this loss of genetic diversity will depend on rates of migration and range contraction (Arenas et al., 2012). In these cases, reductions in genetic diversity may then decrease the ability of species to adapt to further climate change or other global changes. Climate change may also compound losses of genetic diversity that are already occurring due to other global changes such as the introduction of alien species or habitat fragmentation (Winter et al., 2009; see also Section 4.2.4.6).

4.3.2.5.5. Observed global extinctions

Global species extinctions, many of them caused by human activities, are now occurring at rates that approach or exceed the upper limits of

observed natural rates of extinction in the fossil record (Barnosky et al., 2011). However, across all taxa there is only *low confidence* that rates of species extinctions have increased over the last several decades (birds: Szabo et al., 2012; but see Kiesecker, 2011, for amphibians). Most extinctions over the last several centuries have been attributed to habitat loss, overexploitation, pollution, or invasive species, and these are the most important current drivers of extinctions (Millennium Ecosystem Assessment, 2005b; Hofmann and Todgham, 2010; Cahill et al., 2013). Of the more than 800 global extinctions documented by the International Union for Conservation of Nature (IUCN), only 20 have been tenuously linked to recent climate change (Cahill et al., 2013; see also Hoffmann et al., 2010; Szabo et al., 2012). Molluscs, especially freshwater molluscs, have by far the highest rate of documented extinctions of all species groups (Barnosky et al., 2011). Mollusc extinctions are attributed primarily to invasive species, habitat modification, and pollution; changes in climate are rarely evoked as a driver (Lydeard et al., 2004; Regnier et al., 2009; Chiba and Roy, 2011; but see a few cases in Kappes and Haase, 2012; Cahill et al., 2013). Freshwater fish have the highest documented extinction rates of all vertebrates, and again very few have been attributed to changing climate, even tenuously (Burkhead, 2012; Cahill et al., 2013). In contrast, changes in climate have been identified as one of the key drivers of extinctions of amphibians (Pounds et al., 2006). There have been more than 160 probable extinctions of amphibians documented over the last 2 decades, many of them in Central America (Pounds et al., 2006; Kiesecker, 2011). The most notable cases have been the golden toad (*Bufo perigrinus*) and Monteverde harlequin frog (*Atelopus varius*) of Central America, which belong to a group of amphibians with high rates of extinction previously ascribed to global warming with “very high confidence” (Pounds et al., 2006; Fischlin et al., 2007). This case has raised a number of important issues about attribution because (1) the proximate causes of extinction of these and other Central American frogs appear to be an extremely virulent invasive fungal infection and land use change, with regional changes in climate as a potential contributing factor, and (2) changes in regional climate may have been related to natural climate fluctuations rather than anthropogenic climate change (Sodhi et al., 2008; Lips et al., 2008; Anchukaitis and Evans, 2010; Bustamante et al., 2010; Collins, 2010; Vredenburg et al., 2010; Kiesecker, 2011; McKenzie and Peterson, 2012; McMenamin and Hannah, 2012). Owing to *low agreement* among studies there is only *medium confidence* in detection of extinctions and attribution of Central American amphibian extinctions to climate change. While this case highlights difficulties in attribution of extinctions to recent global warming, it also points to a growing consensus that it is the interaction of climate change with other global change pressures that poses the greatest threat to species (Brook et al., 2008; Pereira et al., 2010; Hof et al., 2011b). Overall, there is *very low confidence* that observed species extinctions can be attributed to recent climate warming, owing to the very low fraction of global extinctions that have been ascribed to climate change and tenuous nature of most attributions.

4.3.2.5.6 Projected future species extinctions

Projections of future extinctions due to climate change have received considerable attention since AR4. AR4 stated with *medium confidence* “that approximately 20–30% of the plant and animal species assessed to date are at increasing risk of extinction as global mean temperatures

exceed a warming of 2–3°C above preindustrial levels” (Fischlin et al., 2007). All model-based analyses since AR4 broadly confirm this concern, leading to *high confidence* that climate change will contribute to increased extinction risk for terrestrial and freshwater species over the coming century (Pereira et al., 2010; Sinervo et al., 2010; Pearson, 2011; Warren et al., 2011, 2012; Bellard et al., 2012; Hannah, 2012; Ihlw et al., 2012; Sekercioglu et al., 2012; Wearn et al., 2012; Foden et al., 2013). Most studies indicate that extinction risk rises rapidly with increasing levels of climate change, but some do not (Pereira et al., 2010). The limited number of studies that have directly compared land use and climate change drivers have concluded that projected land use change will continue to be a more important driver of extinction risk throughout the 21st century (Pereira et al., 2010). There is, however, broad agreement that land use, and habitat fragmentation in particular, will pose serious impediments to species adaptation to climate change as it is projected to reduce the capacity of many species to track climate (see Section 4.3.2.5.3). These considerations lead to the assessment that future species extinctions are a high risk because the consequences of climate change are potentially severe, widespread, and irreversible, as extinctions constitute the permanent loss of unique life forms.

There is, however, low agreement concerning the overall fraction of species at risk, the taxa and places most at risk, and the time scale for climate change-driven extinctions to occur. Part of this uncertainty arises from differences in extinction risks within and between modeling studies: this uncertainty has been evaluated in AR4 and subsequent syntheses (Pereira et al., 2010; Warren et al., 2011; Bellard et al., 2012; Cameron, 2012). All studies project increased extinction risk by the end of the 21st century due to climate change, but as indicated in AR4 the range of estimates is large. Recent syntheses indicate that model-based estimates of the fraction of species at substantially increased risk of extinction due to 21st century climate change range from below 1% to above 50% of species in the groups that have been studied (Pereira et al., 2010; Bellard et al., 2012; Cameron, 2012; Foden et al., 2013). Differences in modeling methods, species groups, and climate scenarios between studies make comparisons between estimates difficult (Pereira et al., 2010; Warren et al., 2011; Cameron, 2012).

Many papers published since AR4 argue that the uncertainty may be even higher than indicated in syntheses of model projections, due to limitations in the ability of current models to evaluate extinction risk (e.g., Kuussaari et al., 2009; Pereira et al., 2010; Dawson et al., 2011; McMahon et al., 2011; Pearson, 2011; Araujo and Peterson, 2012; Bellard et al., 2012; Fordham et al., 2012; Hannah, 2012; Kramer et al., 2012; Zurell et al., 2012; Halley et al., 2013; Moritz and Agudo, 2013). Models frequently do not account for genetic and phenotypic adaptive capacity, dispersal capacity, population dynamics, the effects of habitat fragmentation and loss, community interactions, micro-refugia, and the effects of rising CO₂ concentrations, all of which could play a major role in determining species vulnerability to climate change, causing models to either over- or underestimate risk. In addition, difficulties in model validation, large variation in the climate sensitivity of species groups, and uncertainties about time scales linking extinction risks to range reductions also lead to large uncertainty in model-based estimates of extinction risk.

A variety of studies since AR4 illustrate how accounting for these factors alters estimates of extinction risk. Accounting for biotic interactions

such as pollination or predator-prey networks can increase modeled extinction risks, at least for certain areas and species groups (Schweiger et al., 2008; Urban et al., 2008; Hannah, 2012; Nakazawa and Doi, 2012), or can decrease extinction risk (Menéndez et al., 2008; Pateman et al., 2012). Accounting for climatic variation at fine spatial scales may increase (Randin et al., 2009; Gillingham et al., 2012; Suggitt et al., 2012; Dobrowski et al., 2013; Franklin et al., 2013) or decrease (Trivedi et al., 2008; Engler et al., 2011; Shimazaki et al., 2012) the persistence of small populations under future climate change. Several recent studies indicate that correlative species distribution models (the type of model most frequently used for evaluating species extinction risk) tend to be much more pessimistic concerning plant species range contractions and the inferred extinction risks due to climate change when compared to mechanistic models that explicitly account for the interactions between climate change and protective effects of rising CO₂ concentrations on plants (Morin and Thuiller, 2009; Kearney et al., 2010; Cheaib et al., 2012). Models that account for population dynamics indicate that some species populations, such as those of polar bears (Hunter et al., 2010), will decline precipitously over the course of the next century due to climate change, greatly increasing extinction risk, while others may not (Keith et al., 2008). Phenotypic plasticity in one very well-studied temperate bird population has been estimated to be sufficient to keep extinction risk low even with projected warming exceeding 2–3°C (Vedder et al., 2013), but this and other studies suggest that capacity for adaptation is often substantially lower in species with long generation times (see Section 4.4.1.2). There is evidence that interactions between physiological tolerances and regional climate change will lead to large taxonomic and spatial variation in extinction risk (Deutsch et al., 2008; Sinervo et al., 2010). Even species whose populations are not projected to decline rapidly over the next century can face a substantial “extinction debt,” that is, will be in unfavorable climates that over a period of many centuries are projected to lead to large reductions in population size and increase the risk of extinction (Dullinger et al., 2012). Finally, evidence from the paleontological record indicating very low extinction rates over the last several hundred thousand years of substantial natural fluctuations in climate—with a few notable exceptions such as large land animal extinctions during the Holocene—has led to concern that forecasts of very high extinction rates due entirely to climate change may be overestimated (Botkin et al., 2007; Dawson et al., 2011; Hof et al., 2011a; Willis and MacDonald, 2011; Moritz and Agudo, 2013). However, as indicated in Section 4.2.3, no past climate changes are precise analogs of future climate change in terms of speed, magnitude, and spatial scale; nor did they occur alongside the habitat modification, overexploitation, pollution, and invasive species that are characteristic of the 21st century. Therefore the paleontological record cannot easily be used to assess future extinction risk due to climate change.

4.3.3. Impacts on and Risks for Major Systems

This section covers impacts of climate change on broad categories of terrestrial and freshwater ecosystems of the world. We have placed a particular emphasis on those ecosystems that have high exposure to climate change or that may be pushed past thresholds or “tipping points” by climate change. Two geographical regions of particularly high risk have been identified in recent studies: (1) tropics, due to the limited capacity of species to adapt to moderate global warming and (2) high

northern latitude systems, because temperature increases are projected to be large. There has been a tendency to oppose these two points of view, but there is a high risk in both types of systems, albeit for different reasons (Corlett, 2011). Tropical species, which experienced low inter- and intra-annual climate variability, have evolved within narrow thermal limits, and are already near their upper thermal limits (ectotherms: Deutsch et al., 2008; Huey et al., 2012; birds: Sekercioglu et al., 2012; trees: Corlett, 2011). On this basis, tropical species and ecosystems are predicted to be more sensitive to climate change than species and ecosystems that have evolutionary histories of climatic variability (e.g., Arctic and boreal ecosystems; Beaumont et al., 2011). However, there are physiological, evolutionary, and ecological arguments that tropical species and ecosystem sensitivities to climate change are complex and may not be particularly high compared to other systems (Gonzalez et al., 2010; Corlett, 2011; Laurance et al., 2011; Gunderson and Leal, 2012; Walters et al., 2012). High-latitude systems have the greatest projected exposure to rising temperatures (WGI AR5 Chapter 12; Diffenbaugh and Giorgi, 2012), which all else being equal would put them at higher risk. The greatest degree of recent climate warming has occurred at high northern latitudes (Burrows et al., 2011) and the strongest and clearest signals of recent climate warming impacts on ecosystems come from these regions. A comparison of modeled biome level vulnerability indicated that temperate and high northern latitude systems are also the most vulnerable in the future (Gonzalez et al., 2010).

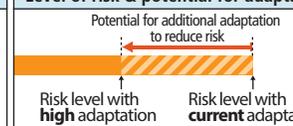
Several potential tipping points (see Section 4.2.1) with regional and global consequences have been identified (Scheffer, 2009); two are elaborated in Boxes 4-3 (Amazon dieback) and 4-4 (tundra-boreal regime shift). An assessment by the authors of this chapter of the top risks in relation to climate change and terrestrial and freshwater ecosystems is presented in Table 4-3.

4.3.3.1. Forests and Woodlands

Forests and woodlands are principal providers of timber, pulp, bioenergy, water, food, medicines, and recreation opportunities and can play prominent roles in cultural traditions. Forests are the habitat of a large fraction of the Earth's terrestrial plant and animal species, with the highest concentrations and levels of endemism found in tropical regions (Gibson et al., 2011). Climate change and forests interact strongly; air temperature, solar radiation, rainfall, and atmospheric CO₂ concentrations are major drivers of forest productivity and forest dynamics, and forests help control climate through the large amounts of carbon they can remove from the atmosphere or release, through absorption or reflection of solar radiation (albedo), cooling through evapotranspiration, and the production of cloud-forming aerosols (Arneth et al., 2010; Pan et al., 2011; Pielke et al., 2011).

Combinations of ground-based observations, atmospheric carbon budgets, and satellite measurements indicate with *high confidence* that forests are currently a net sink for carbon at the global scale. It is estimated that intact and regrowing forests currently contain 860 ± 70 PgC and sequestered 4.0 ± 0.7 PgC yr⁻¹ globally between 2000 and 2007 (WGI AR5 Chapter 6; Canadell et al., 2007; Pan et al., 2011; Le Quéré et al., 2012). The carbon taken up by intact and regrowing forests was counterbalanced by a release due to land use change of 2.8 ± 0.4

Table 4-3 | Key risks for terrestrial and freshwater ecosystems from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three time frames: the present, near term (here, assessed over 2030–2040), and longer term (here, assessed over 2080–2100). For the near term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer term era of climate options, risk levels are presented for global mean temperature increase of 2°C and 4°C above pre-industrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by icons. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions.

Climate-related drivers of impacts				Level of risk & potential for adaptation																					
 Warming trend	 Extreme temperature	 Drying trend	 Precipitation	 <p>Potential for additional adaptation to reduce risk</p> <p>Risk level with high adaptation Risk level with current adaptation</p>																					
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation																					
				Very low	Medium	Very high																			
<p>Reduction in terrestrial carbon sink: Carbon stored in terrestrial ecosystems is vulnerable to loss back into the atmosphere. Key mechanisms include an increase in fire frequency due to climate change and the sensitivity of ecosystem respiration to rising temperatures. (<i>medium confidence</i>)</p> <p>[4.2.4, 4.3.2, 4.3.3]</p>	Adaptation prospects include managing land use (including deforestation), fire, and other disturbances and non-climatic stressors.		<table border="1"> <tr><td>Present</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>Near term (2030–2040)</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>Long term (2080–2100)</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>2°C</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>4°C</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> </table>	Present	Very low	Medium	Very high	Near term (2030–2040)	Very low	Medium	Very high	Long term (2080–2100)	Very low	Medium	Very high	2°C	Very low	Medium	Very high	4°C	Very low	Medium	Very high		
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<p>Boreal tipping point: Arctic ecosystems are vulnerable to abrupt change related to the thawing of permafrost and spread of shrubs in tundra and increase in pests and fires in boreal forests. (<i>medium confidence</i>)</p> <p>[4.3.3.1.1, Box 4-4]</p>	There are few adaptation options in the Arctic.		<table border="1"> <tr><td>Present</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>Near term (2030–2040)</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>Long term (2080–2100)</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>2°C</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>4°C</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> </table>	Present	Very low	Medium	Very high	Near term (2030–2040)	Very low	Medium	Very high	Long term (2080–2100)	Very low	Medium	Very high	2°C	Very low	Medium	Very high	4°C	Very low	Medium	Very high		
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<p>Amazon tipping point: Moist Amazon forests could change abruptly to less carbon-dense drought and fire-adapted ecosystems. (<i>low confidence</i>)</p> <p>[4.3.3.1.3, Box 4-3]</p>	Policy and market measures to reduce deforestation and fire.		<table border="1"> <tr><td>Present</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>Near term (2030–2040)</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>Long term (2080–2100)</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>2°C</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>4°C</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> </table>	Present	Very low	Medium	Very high	Near term (2030–2040)	Very low	Medium	Very high	Long term (2080–2100)	Very low	Medium	Very high	2°C	Very low	Medium	Very high	4°C	Very low	Medium	Very high		
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<p>Tree mortality and forest loss: Tree mortality has been observed to have increased in many places and has been attributed in some cases to direct climate effects and indirect effects due to pests and diseases. The dead trees increase the risk of forest fires. (<i>medium confidence</i>)</p> <p>[4.3.3.1, Box 4-2]</p>	Adaptation options include more effective management of fire, pests, and pathogens.		<table border="1"> <tr><td>Present</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>Near term (2030–2040)</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>Long term (2080–2100)</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>2°C</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>4°C</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> </table>	Present	Very low	Medium	Very high	Near term (2030–2040)	Very low	Medium	Very high	Long term (2080–2100)	Very low	Medium	Very high	2°C	Very low	Medium	Very high	4°C	Very low	Medium	Very high		
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<p>Increased risk of species extinction: A large fraction of the species that have been assessed are vulnerable to extinction as a result of climate change, often in interaction with other threats. Species with an intrinsically low dispersal rate, especially when occupying flat landscapes where the projected climate velocity is high, and species in isolated habitats such as mountain tops, islands, or small protected areas are especially at risk. Cascading effects through organism interactions, and especially those vulnerable to timing (phenological) changes, amplify the risk. (<i>high confidence</i>)</p> <p>[4.3.2.5, 4.3.3.3, 4.3.2.1, 4.4.2]</p>	Adaptation options include reducing habitat modification, habitat fragmentation, pollution, over-exploitation, and invasive species; protected area expansion, assisted dispersal, <i>ex situ</i> conservation.		<table border="1"> <tr><td>Present</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>Near term (2030–2040)</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>Long term (2080–2100)</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>2°C</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>4°C</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> </table>	Present	Very low	Medium	Very high	Near term (2030–2040)	Very low	Medium	Very high	Long term (2080–2100)	Very low	Medium	Very high	2°C	Very low	Medium	Very high	4°C	Very low	Medium	Very high		
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4°C	Very low	Medium	Very high																						
<p>Invasion by non-native species: Disruptions of species interactions and the increase in physiological stress as a result of being near the edge or outside of the historical climate niche increases the vulnerability of ecosystems to invasion by non-native (alien) species, especially in the presence of increased long-distance dispersal opportunities. In the extreme this can result in biome shifts, with consequent changes in the spectrum of ecosystem services provided. (<i>high confidence</i>)</p> <p>[4.2.4.6]</p>	Climate is one driver among many. Adaptation options are limited, largely based on reducing other stresses and measures to slow the unintended arrival of aliens. Intensive direct intervention in controlling emergent invasive species is an option, but could be overwhelmed by the rapidly rising number of cases.		<table border="1"> <tr><td>Present</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>Near term (2030–2040)</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>Long term (2080–2100)</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>2°C</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> <tr><td>4°C</td><td>Very low</td><td>Medium</td><td>Very high</td></tr> </table>	Present	Very low	Medium	Very high	Near term (2030–2040)	Very low	Medium	Very high	Long term (2080–2100)	Very low	Medium	Very high	2°C	Very low	Medium	Very high	4°C	Very low	Medium	Very high		
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PgC yr⁻¹ over this same period due mostly to tropical deforestation and forest degradation associated with logging and fire, resulting in a net carbon balance for global forests of 1.1±0.8 PgC yr⁻¹.

The future of the interaction between climate and forests is unclear. The carbon taken up by intact and regrowing forests appears to have

stabilized compared to the 1990s, after having increased in the 1970s and 1980s (Canadell et al., 2007; Pan et al., 2011). There is *medium confidence* that the terrestrial carbon sink is weakening. The drivers behind the forest carbon sink vary greatly across regions. They include forest regrowth and stimulation of carbon sequestration by climate change, rising atmospheric CO₂ concentrations, and nitrogen deposition

(Pan et al., 2011; see also Sections 4.2.4.1, 4.2.4.2, 4.2.4.4). Most models suggest that rising temperatures, drought, and fires will lead to forests becoming a weaker sink or a net carbon source before the end of the century (Sitch et al., 2008; Bowman et al., 2009). Fires play a dominant role in driving forest dynamics in many parts of the world; forest susceptibility to fire is projected to change little for the lowest emissions scenario (RCP2.6), but substantially for the high emissions scenario (RCP8.5; Figure 4-6). There is *low agreement* on whether climate change will cause fires to become more or less frequent in individual locations (Figure 4-6). Climate change-mediated disease and insect outbreaks could exacerbate climate-driven increases in fire susceptibility (Kurz et al., 2008). The greatest risks for large positive feedbacks from forests to climate through changes in disturbance regimes arise from widespread tree mortality and fire in tropical forests and low-latitude areas of boreal forests, as well as northward expansion of boreal forests into Arctic tundra (Lenton et al., 2008; Kriegler et al., 2009; Good et al., 2011b).

Recent evidence suggests (*low confidence*) that the stimulatory effects of global warming and rising CO₂ concentrations on tree growth may have already peaked in many regions (Charru et al., 2010; Silva et al., 2010; Silva and Anand, 2013) and that warming and changes in precipitation are increasing tree mortality in a wide range of forest systems, acting via heat stress, drought stress, pest outbreaks, and a wide range of other indirect impact mechanisms (Allen, C.D. et al., 2010; Box 4-2). Detection of a coherent global signal is hindered by the lack of long-term observations in many regions and attribution to climate change is difficult because of the multiplicity of mechanisms mediating mortality (Allen, C.D. et al., 2010).

Deforestation has slowed over the last decade (Meyfroidt and Lambin, 2011). This includes substantial reductions in tropical deforestation in some regions, such as the Brazilian Amazon, where deforestation rates declined rapidly after peaking in 2005 (Nepstad et al., 2009; INPE, 2013). Growing pressure for new crop (Section 4.4.4) and grazing land will continue to drive tropical deforestation (*medium confidence*), although recent policy experiments and market-based interventions in land use demonstrate the potential to reduce deforestation (Meyfroidt and Lambin, 2011; Westley et al., 2011; Nepstad et al., 2013).

4.3.3.1.1. Boreal forests

Most projections suggest a poleward expansion of forests into tundra regions, accompanied by a general shift in composition toward more temperate plant functional types (e.g., evergreen needleleaf being replaced by deciduous broadleaf; or in colder regions, deciduous needleleaf replaced by evergreen needleleaf (Lloyd et al., 2011; Pearson et al., 2013). Projections of climate-driven changes in boreal forests over the next few centuries remain uncertain on some issues, partly as a result of different processes of change being considered in different models. In particular, the inclusion or exclusion of fire and insects makes a big difference, possibly making the boreal forest more susceptible to a rapid, nonlinear, or abrupt decline in some regions (Bernhardt et al., 2011; Mann et al., 2012; Scheffer et al., 2012; see WGI AR5 Chapter 12). Recent observed change (Box 4-2) and dynamic vegetation modeling (e.g., Sitch et al., 2008) suggest that regions of the boreal forest could experience widespread forest dieback, although there is *low confidence*

owing to conflicting results (Sitch et al., 2008; Gonzalez et al., 2010) and poor understanding of relevant mechanisms (WGI AR5 Section 12.5.5.6). If such shifts were to occur, they would put the boreal carbon sink at risk (Pan et al., 2011; Mann et al., 2012).

Whereas boreal forest productivity has been expected to increase as a result of warming (Hari and Kulmata, 2008; Bronson et al., 2009; Zhao and Running, 2010; Van Herk et al., 2011), and early analyses of satellite observations confirmed this trend in the 1980s (*medium confidence*), more recent and longer-term assessments indicate with *high confidence* that many areas of boreal forest have instead experienced productivity declines (*high confidence*; Goetz et al., 2007; Parent and Verbyla, 2010; Beck, P.S.A. et al., 2011; de Jong et al., 2011). The best evidence to date indicates that these “browning trends” are due to warming-induced drought, specifically the greater drying power of air (vapor pressure deficit; Williams et al., 2013), inducing photosynthetic down-regulation of boreal tree species, particularly conifer species, most of which are not adapted to the warmer conditions (Welp et al., 2007; Bonan, 2008; Van Herk et al., 2011). Satellite evidence for warming-induced productivity declines has been corroborated by tree ring studies (Barber et al., 2000; Hogg et al., 2008; Beck, P.S.A. et al., 2011; Porter and Pisaric, 2011; Griesbauer and Green, 2012) and long-term tree demography plots in more continental and densely forested areas (Peng et al., 2011; Ma et al., 2012). Conversely, productivity has increased at the boreal-tundra ecotone, where more mesic (moist) conditions may be generating the expected warming-induced positive growth response (Rupp et al., 2001; McGuire et al., 2007; Goldblum and Rigg, 2010; Beck, P.S.A. et al., 2011). The complexity of boreal forest response also involves tree age and size, with younger trees and stands perhaps being more able to benefit from warming where other factors are not limiting (Girardin et al., 2011, 2012).

Where they occur, warming and drying, coupled with productivity declines, insect disturbance, and associated tree mortality, also favor greater fire disturbance (*high confidence*). The boreal biome fire regime has intensified regionally in recent decades, exemplified by increases in the extent of area burned but also a longer fire season and more episodic fires that burn with greater energy output or intensity (Girardin and Mudelsee, 2008; Macias Fauria and Johnson, 2008; Kasischke et al., 2010; Turetsky et al., 2011; Mann et al., 2012; Girardin et al., 2013a). The latter is particularly important because more severe burning consumes soil organic matter to greater depth, often to mineral soil, providing conditions that favor recruitment of deciduous species that in some regions of the North American boreal forest replace what was previously evergreen conifer forest (Johnstone et al., 2010; Bernhardt et al., 2011). Fire-mediated composition changes in post-fire succession influence a host of ecosystem feedbacks to climate, including changes in net ecosystem carbon balance (Bond-Lamberty et al., 2007; Goetz et al., 2007; Welp et al., 2007; Euskirchen et al., 2009) as well as albedo and energy balance (Randerson et al., 2006; Jin et al., 2012; O'Halloran et al., 2012). The extent to which the net effect of these feedbacks will exacerbate or mitigate additional warming is not well known over the larger geographic domain of the boreal biome, except via modeling studies that are relatively poorly constrained owing to sparse *in situ* observations.

The vulnerability of the boreal biome to this cascading series of interacting processes (Wolken et al., 2011), and their ultimate influence on climate

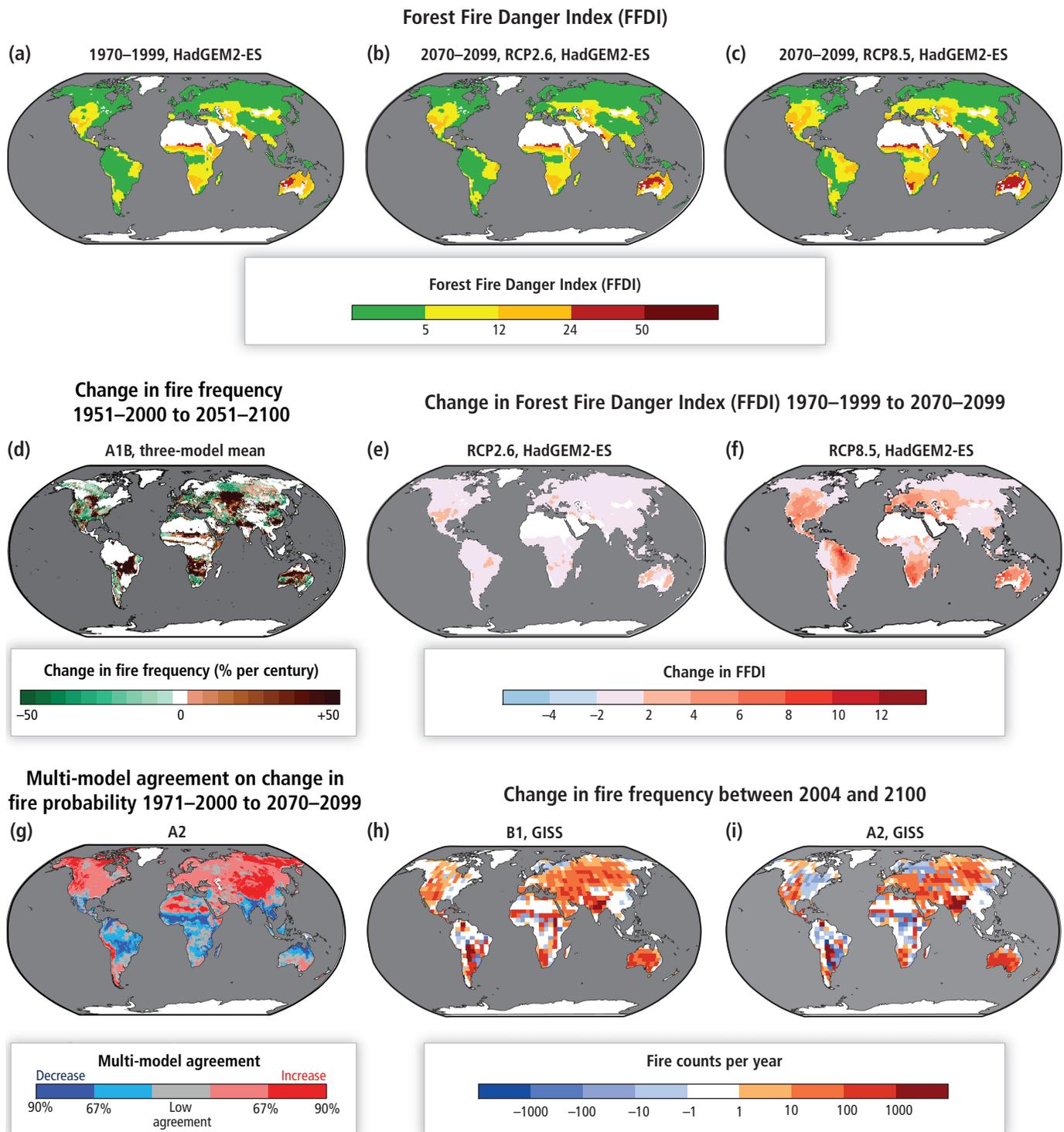


Figure 4-6 | Projected changes in meteorological fire danger, fire probability, and fire frequency with different methods and climate models. (a) 30-year annual mean McArthur Forest Fire Danger Index (FFDI) and change simulated with the Hadley Centre Global Environmental Model version 2 Earth System configuration (HadGEM2-ES) for 1970–1999, with areas of no vegetation excluded (Betts et al., 2013). (b) As (a) for 2070–2099, Representative Concentration Pathway 2.6 (RCP2.6). (c) As (a) for 2070–2099, RCP8.5. (d) Change in fire frequency by 2051–2100 relative to 1951–2000, SRES A1B, simulated with the MC1 vegetation model driven by three GCMs (Commonwealth Scientific and Industrial Research Organisation (CSIRO)-Mk3.0, Met Office Hadley Centre Coupled Model version 3 (HadCM3), Model for Interdisciplinary Research On Climate (MIROC) 3.2medres; mean over three simulations; Gonzalez et al., 2010). (e) Difference between (b) and (a): change in FFDI by 2070–2099 relative to 1970–1999 in HadGEM2-ES, RCP2.6. (f) Difference between (c) and (a): change in FFDI by 2070–2099 relative to 1970–1999 in HadGEM2-ES, RCP8.5. (g) Agreement on changes in fire probability by 2070–2099 relative to 1971–2000 (Moritz et al., 2012) simulated with a statistical model using climate projections from 16 Coupled Model Intercomparison Project Phase 3 (CMIP3) GCMs, Special Report on Emission Scenarios (SRES) A2. (h) Change in fire frequency by 2100 relative to 2004, SRES B1, simulated using climate and land cover projections from the Goddard Institute of Space Studies General Circulation Model (GISS GCM) (AR4 version) and Integrated Model to Assess the Global Environment Integrated Assessment Model (IMAGE IAM) (Pechony and Shindell, 2010). (i) As (h) for SRES A2. Changes in FFDI (a), (b), (c), (e), (f) and fire probability (g) arise entirely from changes in meteorological quantities, whereas changes in fire frequency (d), (h), (i) depend on both meteorological quantities and vegetation.

feedbacks, differs between North America and northern Eurasia (*high confidence*). The latter is dominated by deciduous conifer (larch) forest, extending from western Russia across central to eastern Siberia—a region more than twice the size of the North American boreal biome, most of it underlain by permafrost. In terms of post-fire succession analogous to the North American boreal biome, larch function more like deciduous species than evergreen conifers, with greater density and biomass gain in more severely burned areas, given adequate seed survival through fire events or post-fire seed dispersal (Zyryanova, 2007; Osawa et al., 2010; Alexander et al., 2012). Although the fire regime has intensified in the last 100 years in Siberia, as well as in parts of North America (Soja et al., 2007; Ali et al., 2012; Mann et al., 2012; Marlon et al., 2013), the likelihood of regime shifts in larch forests is currently unknown, partly because larch are self-replacing (albeit at different densities) and partly because it is largely dependent on the fate of permafrost across the region. In summary, an increase in tree mortality is observed in many boreal forests, with the clearest indicators of this in North America. However, tree health in boreal forests varies greatly among regions, which coupled with insufficient temporal coverage means that there is *low confidence* in the detection and attribution of a clear temporal trend in tree mortality at the global scale (Figure 4-4).

The vulnerability of permafrost to thawing and degradation with climate warming is critical not only for determining the rate of a boreal-tundra biome shift and its associated net feedback to climate, but also for predicting the degree to which the mobilization of very large carbon stores frozen for centuries could provide additional warming (*high confidence*; Schuur et al., 2008, 2009, 2013; Tarnocai et al., 2009; Romanovsky et al., 2010; Schaefer et al., 2011; see WGI AR5 Chapters 6 and 12; see also Section 4.3.3.4). The extent and rate of permafrost degradation varies with temperature gradients from warmer discontinuous permafrost areas to colder, more continuous areas, but also with the properties of the soil composition and biology (e.g., Mackelprang et al., 2011). The degree of thermokarsting (melting of ice-rich soil) associated with different substrates and associated topographic relief is variable because boreal vegetation in later successional stages (evergreen conifers in North America) insulates permafrost from air temperature increases; soils with differing silt and gravel content tend to have different ice content that, when melted, produces different degradation and deformation rates; and because of other factors such as the reduction of insulation provided by vegetation cover and soil organic layers due to increased fire (Jorgenson et al., 2010; Grosse et al., 2011). This variability and vulnerability is poorly represented in ESMs (McGuire et al., 2012) and is thus the emphasis of research initiatives currently underway. Carbon management strategies to keep permafrost intact, for example, by removing forest cover to expose the land surface to winter temperatures (Zimov et al., 2009), are impractical, not only because of the vast spatial domain underlain by permafrost, but also because of the broad societal and ecological impacts that would result.

4.3.3.1.2. Temperate forests

The largest areas of temperate forest are found in eastern North America, Europe, and eastern Asia. The overall trend for forests in these regions has until recently been an increase in growth rates of trees and in total carbon stocks. This has been attributed to a combination of increasing

growing season length, rising atmospheric CO₂ concentrations, nitrogen deposition, and forest management—specifically regrowth following formerly more intensive harvesting regimes (Ciais et al., 2008). The relative contribution of these factors has been the subject of substantial and unresolved debate (Boisvenue and Running, 2006). Most temperate forests are managed such that any change is and will be to a large extent anthropogenic.

The world's temperate forests act as an important carbon sink (*high confidence* due to *robust evidence* and *high agreement*), absorbing 0.70 ± 0.08 PgC yr⁻¹ from 1990 to 1999 and 0.80 ± 0.09 from 2000 to 2007 (Pan et al., 2011). This represents 34% of global carbon accumulation in intact forests and 65% of the global net forest carbon sink (total sink minus total emissions from land use).

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

At the biome level, there remains considerable uncertainty in the sign and the magnitude of the carbon cycle response of temperate forests to climate change. A comparison of Dynamic Global Vegetation Models (DGVMs) showed that for identical end of 21st century climate projections, temperate forests are variously projected to substantially increase in total (biomass plus soil) carbon storage, especially through gains in forest cover; or decrease due to reductions in total carbon storage per hectare and loss of tree cover (Sitch et al., 2008). Projections for eastern Asia are less variable: temperate forests remain carbon sinks over the coming century, with carbon storage generally peaking by mid-century and then declining (Sitch et al., 2008; Peng et al., 2009; Ni, 2011). However, regional vegetation models for China predict a substantial northward shift of temperate forest (Weng and Zhou, 2006; Ni, 2011). There is little indication from either models or observations that the responses of temperate forests to climate change

Box 4-2 | Tree Mortality and Climate Change

Extensive tree mortality and widespread forest dieback (high mortality rates at a regional scale) linked to drought and temperature stress have been documented recently on all vegetated continents (Allen, C.D. et al., 2010; Figure 4-7). However, appropriate field data sets are currently lacking for many regions (Anderegg et al., 2013a), leading to *low confidence* in our ability to detect a global trend. Nevertheless, long-term increasing tree mortality rates associated with temperature increases and drought have been documented in boreal and temperate forests in western North America (van Mantgem et al., 2009; Peng et al., 2011). Increased levels of tree mortality following drought episodes have also been detected in multiple tropical forests (Kraft et al., 2010; Phillips et al., 2010) and Europe (Carnicer et al., 2011). Episodes of widespread dieback (high mortality rates at a regional scale) have been observed in multiple vegetation types, particularly in western North America, Australia, and southern Europe (Raffa et al., 2008; Carnicer et al., 2011; Anderegg et al., 2013a). Some widespread dieback events have occurred concomitant with infestation outbreaks (Hogg et al., 2008; Raffa et al., 2008; Michaelian et al., 2011), where insect populations are also directly influenced by climate, such as population release by warmer winter temperatures (Bentz et al., 2010). Although strong attribution of extensive tree mortality to recent warming has been made in a few studies, the paucity of long-term studies of the mechanisms driving mortality means that there is low confidence that this attribution can be made at the global scale.

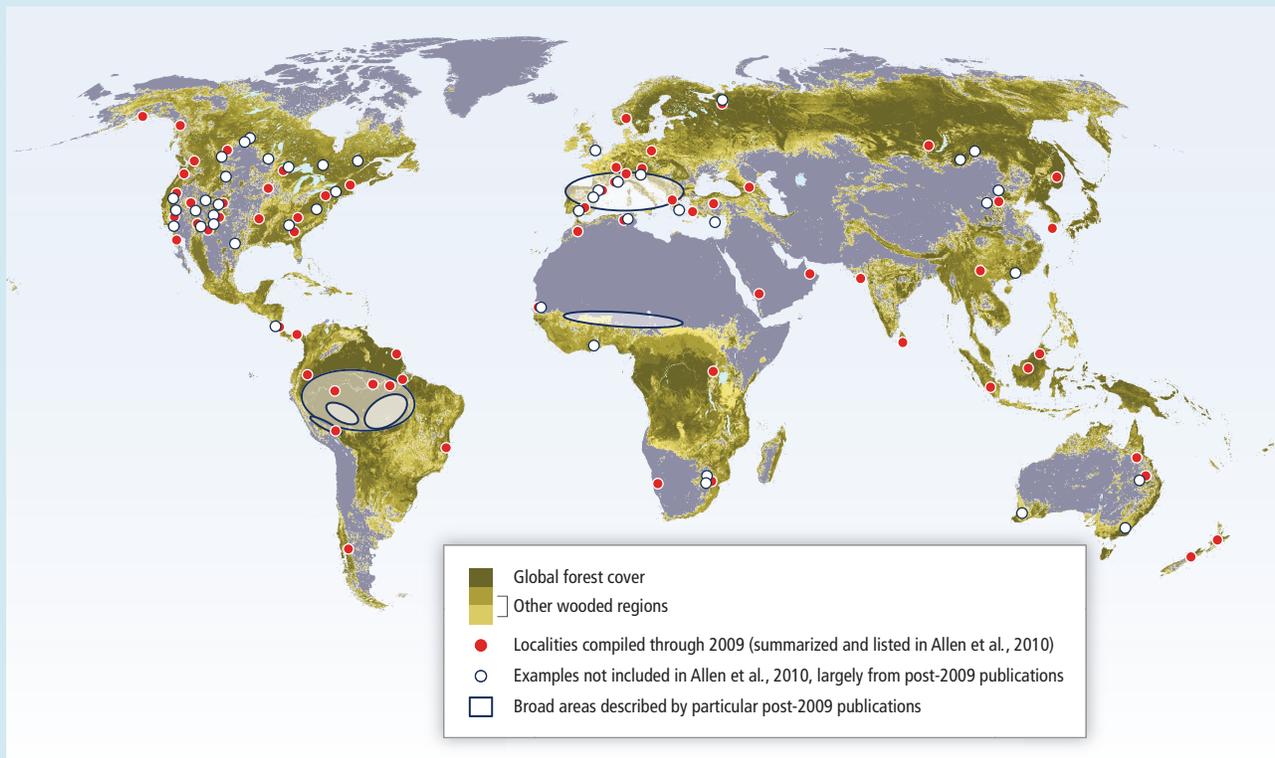


Figure 4-7 | Locations of substantial drought- and heat-induced tree mortality around the globe since 1970 (global forest cover and other wooded regions based on FAO, 2005). Studies compiled through 2009 (red dots) are summarized and listed in Allen, C.D. et al. (2010). Localities and measurement networks not included in Allen, C.D. et al. (2010), which are largely from post-2009 publications, have been added to this map (white dots and shapes). New locality references by region: Africa: Mehl et al., 2010; van der Linde et al., 2011; Fauset et al., 2012; Gonzalez et al., 2012; Kherchouche et al., 2012; Asia: Dulamsuren et al., 2009; Kharuk et al., 2013; Liu et al., 2013; Zhou et al., 2013; Australasia: Brouwers et al., 2012; Fensham et al., 2012; Keith et al., 2012; Matusick et al., 2012; Brouwers et al., 2013; Matusick et al., 2013; Europe: Innes, 1992; Peterken and Mountford, 1996; Linares et al., 2009; Galiano et al., 2010; Vennetier and Ripert, 2010; Aakala et al., 2011; Carnicer et al., 2011; Linares et al., 2011; Sarris et al., 2011; Marini et al., 2012; Cailleret et al., 2013; Vilà-Cabrera et al., 2013; North America: Fahey, 1998; Minnich, 2007; Klos et al., 2009; Ganey and Vojta, 2011; Michaelian et al., 2011; Peng et al., 2011; DeRose and Long, 2012; Fellows and Goulden, 2012; Kaiser et al., 2012; Millar et al., 2012; Garrity et al., 2013; Kukowski et al., 2013; Williams et al., 2013; Worrall et al., 2013; South America: Enquist and Enquist, 2011; Lewis et al., 2011; Saatchi et al., 2013.

Continued next page →

Box 4-2 (continued)

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

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

are characterized by tipping points (Bonan, 2008). There is *low confidence (medium evidence, low agreement)* on long-term, climate-driven changes in temperate forest biomass and geographical range shifts.

At the species level, models predict that the potential climatic space for most tree species will shift poleward and to higher altitude in response to climate change (Dale et al., 2010; Ogawa-Onishi et al., 2010; Hickler et al., 2012). Associated long-term projected range shifts generally vary from several kilometers to several tens of kilometers per decade, most probably faster than natural migration (e.g., Chmura et al., 2011; see also Section 4.3.2.5). Therefore, assisted migration has been suggested as an adaptation measure (see Section 4.4.2.4). Such shifts would alter biodiversity and ecosystem services from temperate forests (e.g., Dale et al., 2010). Multi-model comparisons for temperate forests, however, illustrate that there are differences in species response and that models differ greatly in the severity of projected climate change impacts on species ranges (Morin and Thuiller, 2009; Kearney et al., 2010; Kramer et al., 2010; Cheaib et al., 2012). Tree growth models project increased tree growth at the poleward and high altitudinal range limits over most of the 21st century in China (Ni, 2011). New approaches to modeling tree responses, based on the sensitivity of key life-history stages, suggest that climate change impacts on reproduction could be a major limitation on temperate tree distributions (Morin et al., 2007). Comparisons with paleoecological data have helped improve confidence in the ability of models to project future changes in species ranges (Pearman et al., 2008; Allen, J.R.M. et al., 2010; Garreta et al., 2010). Model projections are qualitatively coherent with observations that temperate forest species are moving up in altitude, probably due to climate warming at the end of the 20th century (Lenoir et al., 2008). There is *medium confidence (medium evidence, medium agreement)* that temperate tree species are migrating poleward and to higher altitudes.

4.3.3.1.3. Tropical forests

Climate change effects on tropical forests interact with the direct influences of humans and are understood largely through field studies of the responses of forests to extreme weather events and through models that are able to simulate a growing number of ecological and atmospheric processes (Malhi et al., 2008; Davidson et al., 2012).

A key uncertainty in our understanding of future impacts of climate change on tropical forests is the strength of direct CO₂ effects on photosynthesis and transpiration (see Section 4.3.2.4). These responses will play an important role in determining tropical forest trends as temperatures and atmospheric CO₂ concentrations rise. There is a physiological basis for arguing that photosynthesis will increase sufficiently to offset the inhibitory effects of higher temperatures on forest productivity (Lloyd and Farquhar, 2008), although heightened photosynthesis does not necessarily translate into an increase in overall forest biomass (Körner and Basler, 2010). DGVMs and the current generation of ESMs, including those used within CMIP5 (e.g., Jones et al., 2011; Powell et al., 2013), generally use formulations for CO₂ effects on photosynthesis and transpiration based on laboratory-scale work (Jarvis, 1976; Farquhar et al., 1980; Ball et al., 1987; Stewart, 1988; Collatz et al., 1992; Leuning, 1995; Haxeltine and Prentice, 1996; Cox et al., 1998) that predates larger ecosystem-scale studies, although some models have been calibrated on the basis of more recent data (Jones et al., 2011).

A second important source of uncertainty is the rate of future CO₂ rise and climate change (Betts et al., 2012). Modeled simulations of future climate in tropical forest regions indicate with *high confidence (robust evidence, high agreement)* that temperature will increase. Future precipitation change, in contrast, is highly uncertain and varies considerably between

climate models (WGI AR5 Annex 1: Atlas of Global and Regional Climate Projections), although there is *medium confidence (medium evidence, medium agreement)* that some tropical regions, such as the eastern Amazon Basin, will experience lower precipitation and more severe drought (Malhi et al., 2009a; Shiogama et al., 2011). The range of possible shifts in the moist tropical forest envelope is large, sensitive to the responsiveness of water use efficiency (WUE) to rising concentrations of atmospheric CO₂, and varies depending on the climate and vegetation model that is used (Scholze et al., 2006; Sitch et al., 2008; Zelazowski et al., 2011). Recent model studies (Malhi et al., 2009a; Cox et al., 2013; Huntingford et al., 2013) indicate that the future geographical range of moist tropical forests as determined by its shifting climatological envelope is less likely to undergo major retractions or expansions by 2100 than was suggested in AR4. Since AR4, there is new evidence of more frequent severe drought episodes in the Amazon region that are associated with sea surface temperature increases in the tropical North Atlantic (*medium confidence*; Marengo et al., 2011). There is *low confidence*, however, that these droughts or the observed sea surface temperatures can be attributed to climate change.

Networks of long-term forest plots reveal that lianas and fast-growing tree species are increasing, as is forest biomass (Phillips et al., 2002, 2005; Lewis et al., 2009a,b, 2011). Faster tree growth is consistent with increasing WUE associated with the rising concentration of CO₂, but also with changes in solar radiation and the ratio of diffuse to direct radiation (Lewis et al., 2009a; Mercado et al., 2009; Brando et al., 2010; see also Section 4.2.4.5). There is *low confidence (limited evidence, medium agreement)* that the composition and biomass of Amazon and African forests are changing through the rise in atmospheric CO₂. The potential suppression of photosynthesis and tree growth in tropical forests through rising air temperatures is supported by physiological and eddy covariance studies (Doughty and Goulden, 2008; Lloyd and Farquhar, 2008; Wood et al., 2012), but is not yet observed as changes in forest biomass (except Clark et al., 2003).

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

There is also a growing body of evidence that severe weather events interact with land use to influence moist tropical forest fire regimes. Many moist tropical forests are not susceptible to fire during typical rainfall years because of high moisture content of fine fuels (Cochrane, 2003). Selective logging, drought, and fire itself can reduce this fire resistance by killing trees, thinning the canopy, and allowing greater

heating of the forest interior (Uhl and Kauffman, 1990; Curran et al., 2004; Ray et al., 2005; Box 4-3). Land use also often increases the ignition sources in tropical landscapes (Silvestrini et al., 2011). These relationships are not yet represented fully in coupled climate-vegetation models. There is *high confidence (robust evidence, high agreement)* that forest fire frequency and severity is increasing through the interaction between severe droughts and land use. There is *medium confidence (medium evidence, high agreement)* that tree mortality in the Amazon region is increasing through severe drought and increased forest fire occurrence and *low confidence* that this can be attributed to warming (Figure 4-4).

Dry tropical forests are defined by strong seasonality in rainfall distribution (Mooney et al., 1995) and have been reduced to an estimated 1 million km² globally through human activities (Miles et al., 2006). Half of the world's remaining dry tropical forests are located in South America. Using five climate model simulations for the 2040–2069 period under the IS92a “business-as-usual scenario,” Miles et al. (2006) found that approximately one-third of the remaining area of tropical dry forests in the Americas will be exposed to higher temperatures and lower rainfall through climate change. Climate change, deforestation, fragmentation, fire, or human pressure place virtually all (97%) of the remaining tropical dry forests at risk of replacement or degradation (Miles et al., 2006). In a regional study a dynamic vegetation model (Integrated Biosphere Simulator (IBIS)) under A2 and B2 scenarios projected by a global climate model (Hadley Centre Regional Model 3 (HadRM3)) found that most of the dry forests of India would be outside of their climate envelopes later in this century (Chaturvedi et al., 2011). There is *low confidence* in our understanding of climate change effects on dry forests globally.

4.3.3.2. Dryland Ecosystems: Savannas, Shrublands, Grasslands, and Deserts

The following sections treat a wide range of terrestrial ecosystems covering a large part of the land surface, whose common features are that they typically exhibit strong water stress for several months each year and grass-like plants and herbs are a major part of their vegetation cover. Thus the principal land use often involves grazing by domestic livestock or wild herbivores.

4.3.3.2.1. Savannas

Savannas are mixtures of coexisting trees and grasses, covering about a quarter of the global land surface, including tropical and temperate forms. Savannas are characterized by annual to decadal fires (Archibald et al., 2009) of relatively low intensity, which are an important factor in maintaining the tree-grass proportions (Beerling and Osborne, 2006), but also constitute a major and climate-sensitive global source of fire-related emissions from land to atmosphere (Schultz et al., 2008; van der Werf et al., 2010). The geographical distribution of savannas is determined by temperature, the seasonal availability of water, fire, and soil conditions (Ellery et al., 1991; Walker and Langridge, 1997; Staver et al., 2011) and is therefore inferred to be susceptible to climate change. In parts of Central Africa, forests have been observed to be

Box 4-3 | A Possible Amazon Basin Tipping Point

Since AR4, our understanding of the potential of a large-scale, climate-driven, self-reinforcing transition of Amazon forests to a dry stable state (known as the Amazon “forest dieback”) has improved. Modeling studies indicate that the likelihood of a climate-driven forest dieback by 2100 is lower than previously thought (Malhi et al., 2009b; Cox et al., 2013; Good et al., 2013; Huntingford et al., 2013), although lower rainfall and more severe drought is expected in the eastern Amazon (Malhi et al., 2009a). There is now *medium confidence (medium evidence, medium agreement)* that climate change alone (i.e., through changes in the climate envelope, without invoking fire and land use) will not drive large-scale forest loss by 2100 although shifts to drier forest types are predicted in the eastern Amazon (Malhi et al., 2009a). Meteorological fire danger is projected to increase in some models (Golding and Betts, 2008; Betts et al., 2013; Figure 4-6). Field studies and regional observations have provided new evidence of critical ecological thresholds and positive feedbacks between climate change and land use activities that could drive a fire-mediated, self-reinforcing dieback during the next few decades (Figure 4-8). There is now *medium confidence (medium evidence, high agreement)* that severe drought episodes, land use, and fire interact synergistically to drive the transition of mature Amazon forests to low-biomass, low-statured fire-adapted woody vegetation.

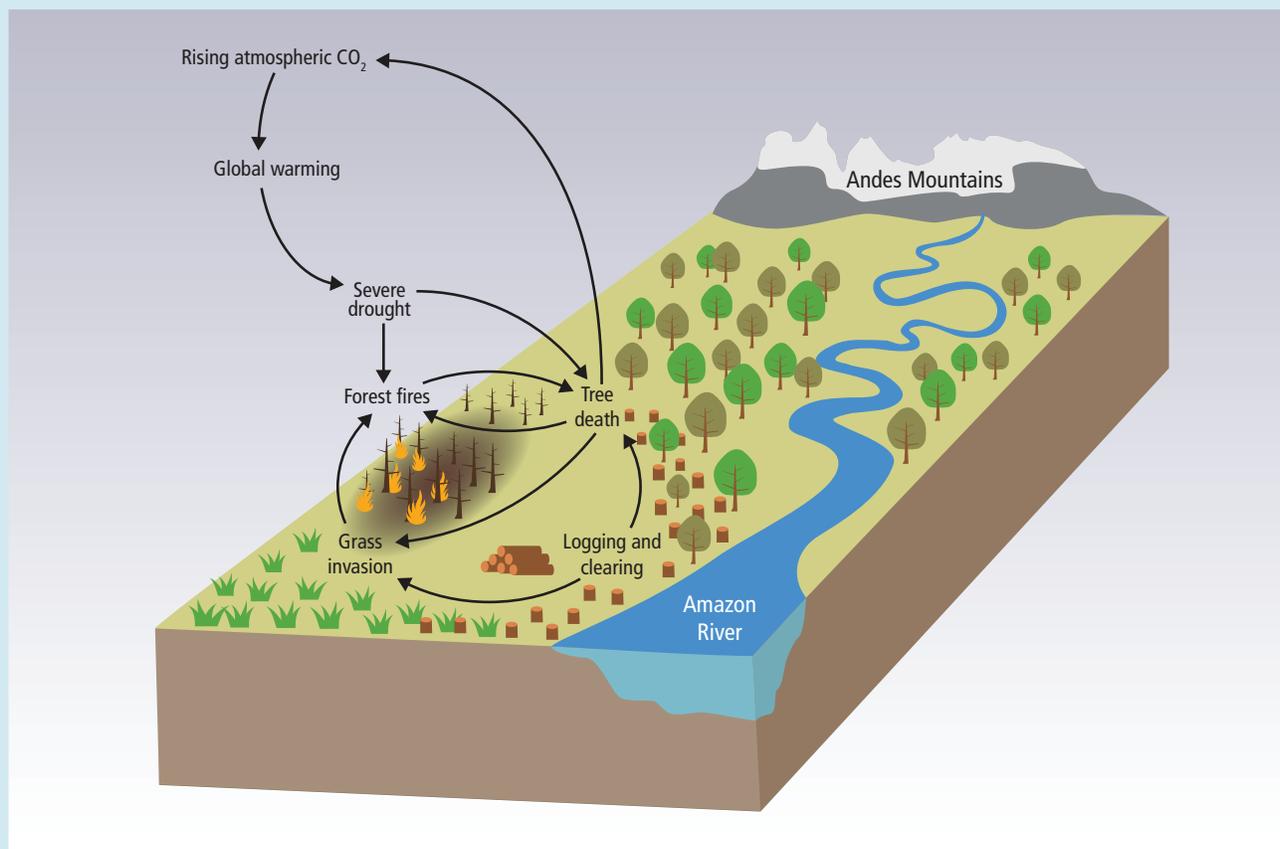


Figure 4-8 | The forests of the Amazon Basin are being altered through severe droughts, land use (deforestation, logging), and increased frequencies of forest fire. Some of these processes are self-reinforcing through positive feedbacks, and create the potential for a large-scale tipping point. For example, forest fire kills trees, increasing the likelihood of subsequent burning. This effect is magnified when tree death allows forests to be invaded by flammable grasses. Deforestation provides ignition sources to flammable forests, contributing to this dieback. Climate change contributes to this tipping point by increasing drought severity, reducing rainfall and raising air temperatures, particularly in the eastern Amazon Basin (*medium confidence; medium evidence, medium agreement*).

Continued next page →

Box 4-3 (continued)

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

Landscape level processes further increase the likelihood of forest fire. Fire ignition sources are more common in agricultural and grazing lands than in forested landscapes (Silvestrini et al., 2011) (*high confidence: robust evidence, high agreement*), and forest conversion to grazing and crop lands can inhibit regional rainfall through changes in albedo and evapotranspiration (Costa et al., 2007; Butt et al., 2011; Knox et al., 2011) (*low confidence: medium evidence, low agreement*) or through smoke, which can inhibit rainfall under some circumstances (Andreae et al., 2004) (*medium confidence: medium evidence, medium agreement*). Apart from these landscape processes, climate change could increase the incidence of severe drought episodes (Mahli et al. 2009b; Shiogama et al., 2011).

If recent patterns of deforestation (through 2005), logging, severe drought, and forest fire continue into the future, more than half of the region's forests will be cleared, logged, burned, or exposed to drought by 2030, even without invoking positive feedbacks with regional climate, releasing 20 ± 10 PgC to the atmosphere (Nepstad et al., 2008) (*low confidence: low evidence, medium agreement*) (Figure 4-8). The likelihood of a tipping point being reached may decline if extreme droughts (such as 1998, 2005, and 2010) (Marengo et al., 2011) become less frequent, if land management fires are suppressed, if forest fires are extinguished on a large scale (Soares-Filho et al., 2012), if deforestation declines, or if cleared lands are reforested (Nepstad et al., 2008). The 77% decline in deforestation in the Brazilian Amazon with 80% of the region's forest still standing (INPE, 2013) demonstrates that policy-led avoidance of a fire-mediated tipping point is plausible.

moving into adjacent savannas and grasslands (Mitchard et al., 2009), possibly due to depopulation and changes in the fire regime. In northern Australia, forest is expanding into former savanna areas (Brook and Bowman, 2006; Bowman et al., 2011; Tng et al., 2012). It has been projected that drying and greater seasonality, acting in conjunction with increased fire, could lead to former forested areas becoming savannas in parts of the Amazon basin (Malhi et al., 2009b; Box 4-3). In many places around the world the savanna boundary is moving into former grasslands on elevation gradients; in other words, into areas inferred to be formerly too cool for trees (Breshears, 2006).

The proportion of trees and grasses in savannas is considered unstable under some conditions (De Michele et al., 2011; Staver et al., 2011). The differential effects of climate change, rising CO₂, fire, and herbivory on trees and grasses have the potential to alter the tree cover in savannas, possibly abruptly. There is evidence from many parts of the world that the tree cover and biomass in savannas has increased over the past century and in some places, on all continents, continues to do so

(*robust evidence, high agreement*; Moleele et al., 2002; Angassa and Oba, 2008; Cabral et al., 2009; Wigley et al., 2009; Witt et al., 2009; Lunt et al., 2010; Rohde and Hoffman, 2012). The general consequences are more carbon stored per unit land area in form of tree biomass and soil organic matter (Hughes et al., 2006; Liao et al., 2006; Knapp et al., 2007; Throop and Archer, 2008; Boutton et al., 2009), changes in hydrology (Muñoz-Robles et al., 2011), and reduced grazing potential (Scholes and Archer, 1997). Increasing tree cover in savannas has been attributed to changes in land management (Joubert et al., 2008; Van Auken, 2009), rising CO₂ (Bond and Midgley, 2012; Buitenwerf et al., 2012), climate variability and change (Eamus and Palmer, 2007; Fensham et al., 2009), or several of these factors acting in combination (Ward, 2005). As yet, there are no studies that definitively attribute the relative importance of the climate- and non-climate-related causes of woody plant biomass increase in savannas (and the invasion of trees into former grasslands), but there is *medium agreement* and *robust evidence* that climate change and rising CO₂ are contributing factors in many cases. The increased growth rate of C₃ photosynthetic system trees relative to C₄

grasses under rising CO₂ could relieve the demographic bottleneck that keeps trees trapped within the flame zone of the grasses, a hypothesis supported by elevated CO₂ experiments with savanna saplings (Kgope et al., 2010).

A model of grasslands, savannas, and forests suggests that rising CO₂ does increase the likelihood of abrupt shifts to woodier states, but the transition will take place at different CO₂ concentrations in different environments (Higgins and Scheiter, 2012). On the other hand, observation of contrasts in the degree of savanna thickening between land parcels with the same CO₂ exposure but different land use histories, topographic position, or soil depth (Wiegand et al., 2005; Wu and Archer, 2005) imply that land management, water balance, and microclimate are also important. Tree cover in savannas is rainfall-constrained (Sankaran et al., 2005), suggesting that future increases in rainfall projected for most but not all savanna areas (WGI AR5 Annex I: Atlas of Global and Regional Climate Projections) could lead to increased tree biomass.

4.3.3.2.2. Grasslands and shrublands

Rangelands (partly overlapping with savannas) cover approximately 30% of the Earth's ice-free land surface and hold an equivalent amount of the world's terrestrial carbon (Booker et al., 2013). Much evidence from around the world shows that dry grasslands and shrublands are highly responsive in terms of primary production, species composition, and carbon balance to changes in water balance (precipitation and evaporative demand) within the range of projected climate changes (*high confidence*) (e.g., Sala et al., 1988; Snyman and Fouché, 1993; Fay et al., 2003; Peñuelas et al., 2004, 2007; Prieto et al., 2009; Peters et al., 2010; Martí-Roura et al., 2011; Booker et al., 2013; Wu and Chen, 2013). Rainfall amount and timing have large effects on a wide range of biological processes in grasslands and shrublands, including seed germination, seedling establishment, plant growth, flowering time, root mass, community composition, population and community dynamics production, decomposition and respiration, microbial processes and carbon, plant, and soil nutrient contents (e.g., Fay et al., 2003; Peñuelas et al., 2004, 2007; Beier et al., 2008; Sardans et al., 2008a,b; Sowerby et al., 2008; Liu et al., 2009; Miranda et al., 2009; Albert et al., 2011, 2012; Selsted et al., 2012; Walter et al., 2012).

Precipitation changes were as important for mountain flora in Europe as temperature changes, and the greatest composition changes will probably occur when decreased precipitation accompany warming (Engler et al., 2011). Responses of shrublands to drought may be driven partly by changes in the soil microbial community (Jensen et al., 2003) or changes in soil fauna (Maraldo et al., 2008). An increase in drought frequency, without an increase in drought severity, leads to loss of soil carbon in moist, carbon-rich moorlands, due to changes in soil structure or soil microbial community leading to increased hydrophobicity and soil respiration (Sowerby et al., 2008, 2010). Simulated increased spring temperature and decreased summer precipitation had a general negative effect on plant survival and plant growth, irrespective of the macroclimatic niche characteristics of the species. Against expectation, species with ranges extending into drier regions did not generally perform better under drier conditions (Bütof et al., 2012).

Changing climate and land use have resulted in increased aridity and a higher frequency of droughts in drylands around the world, with increasing dominance of abiotic controls of land degradation (in contrast to direct human- or herbivore-driven degradation) and changes in hydrology and the erosion of soil by wind (Ravi et al., 2010). In mixed shrub grasslands, the influence of drought periods could produce transient pulses of carbon that are much larger than the pulses produced by fire (Martí-Roura et al., 2011). Most studies of changes in arid systems between grasslands and shrublands have focused on plant-soil feedbacks that favor shrub growth. Summers drier than three-quarters of current rainfall decreased grass seedling recruitment to negligible values (Peters et al., 2010). Management cannot reliably increase carbon uptake in arid and semiarid rangelands, which is most often controlled by abiotic factors not easily changed by management of grazing or vegetation (Booker et al., 2013).

Other factors being equal, grasslands and shrublands in cool areas are expected to respond to warming with increased primary production, while those in hot areas are expected to show decreased production (*limited evidence, low agreement*). A shift to more woody vegetation states expected to occur (locally but not globally) in tropical grasslands of the African continent (Higgins and Scheiter, 2012). The response to warming and drought depends on site, year, and plant species, as shown by manipulation experiments (Peñuelas et al., 2004, 2007; Gao and Giorgi, 2008; Grime et al., 2008; Shinoda et al., 2010; Wu and Chen, 2013). In most temperate and Arctic regions, the capacity to support richer (i.e., more diverse) communities is projected to increase with rising temperature, while decreases in water availability suggest a decline in capacity to support species-rich communities in most tropical and subtropical regions (Sommer et al., 2010). Warming may cause an asymmetrical response of soil carbon and nitrogen cycles, causing nitrogen limitation that reduces acclimation in plant production (Beier et al., 2008).

Some grasslands are exposed to elevated levels of nitrogen deposition, which alters species composition, increases primary production up to a point, and decreases it thereafter (see Section 4.2.4.2; Bobbink et al., 2010; Cleland and Harpole, 2010; Gaudnik et al., 2011). In a study of 162 plots over 25 years, nitrogen deposition drove grassland composition at the local scale, in interaction with climate, whereas climate changes were the predominant driver at the regional scale (Gaudnik et al., 2011). Nitrogen mineralization in shrublands under either arid or wet conditions is more sensitive to periodic droughts than systems under more mesic conditions (Emmett et al., 2004). Decreased tissue concentrations of phosphorus were also associated with warming and drought (Peñuelas et al., 2004, 2012; Beier et al., 2008). Strong interactions between warming and disturbances have been observed, leading to increased nitrogen leaching from shrubland ecosystems (Beier et al., 2004).

Most grasslands and shrublands are characterized by relatively frequent but low-intensity fires, which affect their plant species composition and demographics (e.g., Gibson and Hulbert, 1987; Gill et al., 1999; Uys et al., 2004; de Torres Curth et al., 2012). Species composition changes may be as important in determining ecosystem impacts as the direct effects of climate on plant (Suttle et al., 2007). Fire frequency, duration, and intensity are influenced primarily by climate and secondarily by management (Pitman et al., 2007; Lenihan et al., 2008; Archibald et al.,

2009; Giannakopoulos et al., 2009; Armenteras-Pascual et al., 2011), and are therefore sensitive to climate change; the duration of the fire season is also projected to broaden (Clarke et al., 2013). Changes in fire frequency may interact with changes in rainfall seasonality: for instance, if fires are followed by rainy spring periods in northwestern Patagonia, as occurs with more frequent El Niño-Southern Oscillation (ENSO) phenomena, there are more recruitment windows for shrubs (Ghermandi et al., 2010). Relatively little is known regarding the combined effect of climate change and increased grazing by large mammals, or on the consequences for pastoral livelihoods that depend on rangelands (Thornton et al., 2009).

4.3.3.2.3. Deserts

The deserts of the world, defined as land areas with an arid or hyperarid climate regime, occupy 35% of the global land surface. Species composition in desert areas is expected to shift in response to climate warming (Ooi et al., 2009; Kimball et al., 2010). Deserts are sparsely populated, but the people who do live there are among the poorest in the world (Millennium Ecosystem Assessment, 2005a). There is *medium agreement* but *limited evidence* that the present extent of deserts will increase in the coming decades, despite the projected increase in rainfall at a global scale, as a result of the strengthening of the Hadley Circulation, which determines the location of the broad band of hot deserts approximately 15°N to 30°N and 15°S to 30°S of the equator (Mitas and Clement, 2005; Seidel et al., 2008; Johanson and Fu, 2009; Lu et al., 2009; Zhou et al., 2011). There may be a feedback to the global climate from an increase in desert extent, which differs in sign between deserts closer to the equator than 20° and those closer to the pole: in model simulations, extension of the near-equator “hot deserts” causes warming, while extension of the near-boreal “cold deserts” causes cooling, in both cases largely through albedo-mediated effects (Alkama et al., 2012). Deserts are expected to become warmer and drier at faster rates than other terrestrial regions (Lapola et al., 2009; Stahlschmidt et al., 2011). Most deserts are already extremely hot, and therefore further warming likely to be physiologically injurious rather than beneficial. The ecological dynamics in deserts are rainfall event-driven (Holmgren et al., 2006), often involving the concatenation of a number of quasi-independent events. Some desert tolerance mechanisms (e.g., biological adaptations by long-lived taxa) may be outpaced by global climate change (Lapola et al., 2009; Stahlschmidt et al., 2011).

4.3.3.2.4. Mediterranean-type ecosystems

Mediterranean-type ecosystems occur on most continents, and are characterized by cool, wet winters and hot, dry summers. They were identified as being among the most likely to be impacted by climate change in AR4 and received extensive coverage (Fischlin et al., 2007). Since then, further evidence has accumulated of climate risks to these systems from rising temperature (Giorgi and Lionello, 2008), rainfall change (declining in most but not all cases), increased drought (Sections 23.2.3, 25.2), and increased fire frequency (Section 23.4.4). There have been observed shifts in phenology (Gordo and Sanz, 2010), range contraction of Mediterranean species (Pauli et al., 2012), declines in the

health and growth rate of dominant tree species (Allen, C.D. et al., 2010; Sarris et al., 2011; Brouwers et al., 2012; see also Section 23.4.4), and increased risk of erosion and desertification, especially in very dry areas (Lindner et al., 2010; Shakesby, 2011). Model projections show further species range contractions in the 21st century under all climate change scenarios. This will result in losses of biodiversity (*medium confidence*) (Maiorano et al., 2011; Kuhlmann et al., 2012; see also Sections 23.6.4, 25.1).

4.3.3.3. Rivers, Lakes, Wetlands, and Peatlands

Freshwater ecosystems are considered to be among the most threatened on the planet (Dudgeon et al., 2006; Vörösmarty et al., 2010). Fragmentation of rivers by dams and the alteration of natural flow regimes have led to major impacts on freshwater biota (Pringle, 2001; Bunn and Arthington, 2002; Nilsson et al., 2005; Reidy Liermann et al., 2012). Floodplains and wetland areas have become occupied for intensive urban and agricultural land use to the extent that many are functionally disconnected from their rivers (Tockner et al., 2008). Pollution from cities and agriculture, especially nutrient loading, has resulted in declines in water quality and the loss of essential ecosystem services (Allan, 2004). As a direct consequence of these and other impacts, freshwaters have some of the highest rates of extinction of any ecosystem for those species groups assessed for the IUCN Red List (estimated as much as 4% per decade for some groups, such as crayfish, mussels, fishes, and amphibians in North America) (Dudgeon et al., 2006), with estimates that roughly 10,000 to 20,000 freshwater species are extinct or imperilled as a consequence of human activity (Strayer and Dudgeon, 2010). This is a particular concern given that freshwater habitats support 6% of all described species (Dudgeon et al., 2006), including approximately 40% of the world’s fish diversity and a third of the vertebrate diversity (Balian et al., 2008).

It is *very likely* that these stressors to freshwater ecosystems will continue to dominate as human demand for water resources grows, accompanied by increased urbanization and expansion of irrigated agriculture (Vörösmarty et al., 2000; Malmqvist et al., 2008; Dise, 2009). However, climate change will have significant additional impacts (*high confidence*), from altered thermal regimes, altered precipitation and flow regimes, and, in the case of coastal wetlands, sea level rise. Specific aquatic habitats that are most vulnerable to these direct climate effects, especially rising temperatures, are those at high altitude and high latitude, including Arctic and sub-Arctic bog communities on permafrost, and alpine and Arctic streams and lakes (see Section 4.3.3.4; Klanderud and Totland, 2005; Smith et al., 2005; Smol and Douglas, 2007b). It is noteworthy that these high-latitude systems currently experience a relatively low level of threat from other human activities (Vörösmarty et al., 2010). It is likely that the shrinkage and disappearance of glaciers will lead to the reduction of local and regional freshwater biodiversity, with 11 to 38% of the regional macroinvertebrate species pool expected to be lost following complete disappearance of glaciers (Jacobsen et al., 2012; Box CC-RF). Shrinkage of glaciers and the loss of small glaciers will most likely reduce beta diversity at the species and the genetic level, as predicted for the Pyrenees (Finn et al., 2013). Dryland rivers and wetlands, many already experiencing severe water stress from human consumptive use, are also likely to be further impacted by decreased and more variable

precipitation and higher temperatures. Headwater stream systems in general are also vulnerable to the effects of warming because their temperature regimes closely track air temperatures (Caissie, 2006).

There is widespread evidence of rising stream and river temperatures over the past few decades (Langan et al., 2001; Morrison et al., 2002; Webb and Nobilis, 2007; Chessman, 2009; Ormerod, 2009; Kaushal et al., 2010; van Vliet et al., 2011; Markovic et al., 2013; but see Arismendi et al., 2012). Rising water temperature has been linked by observational and experimental studies to shifts in invertebrate community composition, including declines in cold stenothermic species (Brown et al., 2007; Durance and Ormerod, 2007; Chessman, 2009; Ormerod, 2009). Rising temperature is also implicated in species range shifts (e.g., Comte and Grenouillet, 2013), implying changes in the composition of river fish communities (Daufresne and Boet, 2007; Buisson et al., 2008; Comte et al., 2013), especially in headwater streams where species are more sensitive to warming (e.g., Buisson and Grenouillet, 2009).

Rising temperatures in the well-mixed surface waters in many temperate lakes, resulting in reduced periods of ice formation (Livingstone and Adrian, 2009; Weyhenmeyer et al., 2011) and earlier onset and increased duration and stability of the thermocline during summer (Winder and Schindler, 2004), are projected to favor a shift in dominance to smaller phytoplankton (Parker et al., 2008; Winder et al., 2009; Yvon-Durocher et al., 2011) and cyanobacteria (Wiedner et al., 2007; Jöhnk et al., 2008; Paerl et al., 2011), especially in those ecosystems experiencing high anthropogenic loading of nutrients (Wagner and Adrian, 2009); with impacts to water quality, food webs, and productivity (O'Reilly et al., 2003; Verburg et al., 2003; Gyllström et al., 2005; Parker et al., 2008; Shimoda et al., 2011). Prolonged stratification and associated anaerobic conditions near the sediment-water interface can increase the internal loading of phosphorus, particularly in eutrophic lakes (Søndergaard et al., 2003; Wilhelm and Adrian, 2008; Wagner and Adrian, 2009).

In many freshwater ecosystems, the input of dissolved organic carbon through runoff from the catchment has increased, inducing changes in water color (Hongve et al., 2004; Evans et al., 2005; Erlandsson et al., 2008). Soil recovery from acidification and changed hydrological conditions (partly linked to increased precipitation) appear to be the main factors driving this development (Evans et al., 2005; Monteith et al., 2007). The resulting increased light attenuation can lead to lower algal concentrations and loss of submersed vegetation (Ask et al., 2009; Karlsson et al., 2009).

Emergent aquatic macrophytes are likely to expand their northward distribution and percentage cover in boreal lakes and wetlands, posing an increasing overgrowth risk for sensitive macrophyte species (Alahuhta et al., 2011). Long-term shifts in macroinvertebrate communities have also been observed in European lakes where temperatures have increased (Burgmer et al., 2007), noting that warming may increase species richness in smaller temperate water bodies, especially those at high altitude (Rosset et al., 2010). Although less studied, it has been proposed that tropical ectothermic ("cold blooded") organisms will be particularly vulnerable because they will approach critical maximum temperatures proportionately faster than species in high-latitude environments, despite lower rates of warming (Deutsch et al., 2008; Hamilton, 2010; Laurance et al., 2011).

There is growing evidence that climate-induced changes in precipitation will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (*high confidence* in detection, *medium confidence* in attribution; see Box CC-RF; Xenopoulos et al., 2005; Aldous et al., 2011). Freshwater ecosystems in Mediterranean-montane ecoregions (e.g., Australia, California, and South Africa) are projected to experience a shortened wet season and prolonged, warmer summer season (Klausmeyer and Shaw, 2009), increasing the vulnerability of fish communities to drought (Magalhães et al., 2007; Hermoso and Clavero, 2011) and floods (Meyers et al., 2010). Shifts in hydrologic regimes in snowmelt systems, including earlier runoff and declining base flows in summer (Stewart et al., 2005; Stewart, 2009), are projected to alter freshwater ecosystems, through changes in physical habitat and water quality (Bryant, 2009). Declining rainfall and increased interannual variability will most likely increase low-flow and dry-spell duration in dryland regions, leading to reduced water quality in remnant pools (Dahm et al., 2003), reduction in floodplain egg and seed banks (Capon, 2007; Jenkins and Boulton, 2007), the loss of permanent aquatic refugia for fully aquatic species and water birds (Johnson et al., 2005; Bond et al., 2008; Sheldon et al., 2010), altered freshwater food webs (Ledger et al., 2013), and drying out of wetlands (Davis, J.L. et al., 2010).

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

Peatlands contain large stocks of carbon that are vulnerable to change through land use and climate change. Although peatlands cover only about 3% of the land surface, they hold the equivalent of half of the atmosphere's carbon (as CO₂), or one-third of the world's soil carbon stock (400 to 600 Pg) (Limpens et al., 2008; Frohling et al., 2011; Page et al., 2011). About 14 to 20% of the world's peatlands are currently used for agriculture (Oleszczuk et al., 2008) and many, particularly peat swamp forests in Southeast Asia, are undergoing rapid major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning (Limpens et al., 2008; Hooijer et al., 2010). Deforestation, drainage, and burning in Indonesian peat swamp forests can release $59.4 \pm 10.2 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ over 25 years (Murdiyarto et al., 2010), contributing significantly to global GHG emissions, especially during periods of intense drought associated with ENSO when burning is more common (Page et al., 2002). Anthropogenic disturbance has changed peatlands from being a weak global carbon sink to a source (Frohling et al., 2011), though interannual variability is large. Fluvial export can also be a significant contributor to carbon losses that has been largely overlooked to date, with recent estimates of DOC export from degraded tropical peatlands 50% higher than in intact systems (Moore et al., 2013). Conserving

peatland areas not yet developed for biofuels or other crops, or rewetting and restoring degraded peatlands to preserve their carbon store, are potential mitigation strategies.

Sea level rise will lead to direct losses of coastal wetlands with associated impacts on water birds and other wildlife species dependent on fresh water (BMT WBM, 2010; Pearlstine et al., 2010; Traill et al., 2010), but the impact will probably be relatively small compared with the degree of direct and indirect human-induced destruction (Nicholls, 2004). River deltas and associated wetlands are particularly vulnerable to rising sea level, and this threat is further compounded by trapping of sediment in reservoirs upstream and subsidence from removal of oil, gas, and water (Syvitski et al., 2009; see Section 5.4.2.7). Lower river flows might exacerbate the impact of sea level rise and thus salinization on freshwater ecosystems close to the ocean (Ficke et al., 2007).

4.3.3.4. Tundra, Alpine, and Permafrost Systems

The High Arctic region, with tundra-dominated landscapes, has warmed more than the global average over the last century (Kaufman et al., 2009; see WGI AR5 Chapter 2). Changes consistent with warming are evident in the freshwater and terrestrial ecosystems and permafrost of the region (Hinzman et al., 2005; Axford et al., 2009; Jia, G.J. et al., 2009; Post et al., 2009; Prowse and Brown, 2010; Romanovsky et al., 2010; Walker et al., 2012). Most of the Arctic has experienced recent change in vegetation photosynthetic capacity, particularly adjacent to rapidly retreating sea ice (Bhatt et al., 2010). Changes in terrestrial environments in Antarctica have also been reported. Vieira et al. (2010) show that in the Maritime Antarctic permafrost temperatures are close to thaw. Permafrost warming has been observed in continental Antarctica (Guglielmin and Cannone, 2012) and for the Palmer archipelago (Bockheim et al., 2013).

Continued warming is projected to cause the terrestrial vegetation and lake systems of the Arctic to change substantially (*high confidence*). Continued expansion in woody vegetation cover in tundra regions over the 21st century is projected by the CMIP5 ESMs (Bosio et al., 2012; see WGI AR5 Chapter 6), by dynamic global vegetation models driven by other climate model projections, and by observationally based statistical models (Pearson et al., 2013). Changes may be complex (see Box 4-4) and in some cases involve nonlinear and threshold responses to warming and other climatic change (Hinzman et al., 2005; Mueller, D.R. et al., 2009; Bonfils et al., 2012). Arctic vegetation change is expected to continue long after any stabilization of global mean temperature (see WGI AR5 Chapter 6; Falloon et al., 2012). In some regions, reduced surface albedo due to increased vegetation cover is projected to cause further local warming even in scenarios of stabilized GHG concentrations (Falloon et al., 2012).

In the Arctic tundra biome (in contrast to the boreal forests discussed in Section 4.3.3.1.1), vegetation productivity has systematically increased over the past few decades in both North America and northern Eurasia (Goetz et al., 2007; Stow et al., 2007; Jia, G.J. et al., 2009; de Jong et al., 2011; Myers-Smith et al., 2011; Elmendorf et al., 2012). This phenomenon is amplified by retreat of coastal sea ice (Bhatt et al., 2010) and has been widely discussed in the context of increased

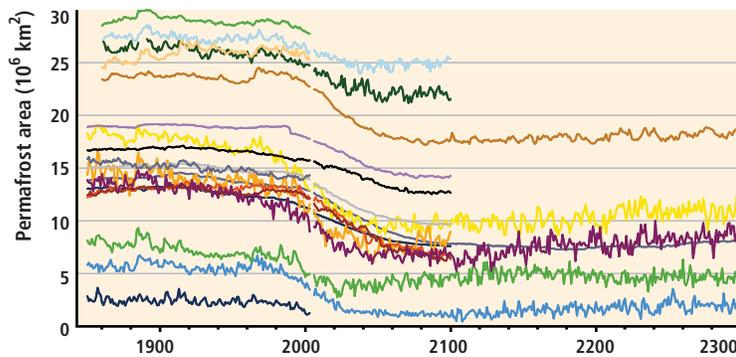
shrub growth and expansion over the last half century (Forbes et al., 2010; Myers-Smith et al., 2011). Deciduous shrubs and graminoids respond to warming with increased growth (Walker, 2006; Epstein et al., 2008; Euskirchen et al., 2009; Lantz et al., 2010). Analyses of satellite time series data show the increased productivity trend is not unique to shrub-dominated tundra areas (Jia, G.J. et al., 2009; Beck and Goetz, 2011); thus greening is a response shared by multiple vegetation communities and continued changes in the tundra biome can be expected irrespective of shrub presence. The very large spatial scale over which these changes are occurring, the strong warming signal over much of the Arctic for the last 5 decades (Burrows et al., 2011), and the absence of strong confounding factors means that detection of these changes in Arctic systems and their attribution to global warming can be made with *high confidence*, despite the relatively short time frame of most observations (Figure 4-4).

Shrub expansion and height changes are particularly important because they trap snow, mediate winter soil temperature and summer moisture regimes, increase nutrient mineralization, and produce a positive feedback for additional shrub growth (Sturm et al., 2005; Lawrence et al., 2007; Bonfils et al., 2012). Although increased shrub cover and height produce shadowing that reduce ground heat flux and active layer depth, they also reduce surface albedo, increase energy absorption and evapotranspiration (Chapin III et al., 2005; Blok et al., 2010), and produce feedbacks that reinforce shrub densification and regional warming (Lawrence and Swenson, 2011; Bonfils et al., 2012). On balance, these feedbacks can act to partially offset one another, but when coupled with warmer and wetter conditions they act to increase active layer depth and permafrost thaw (Yi et al., 2007; Bonfils et al., 2012).

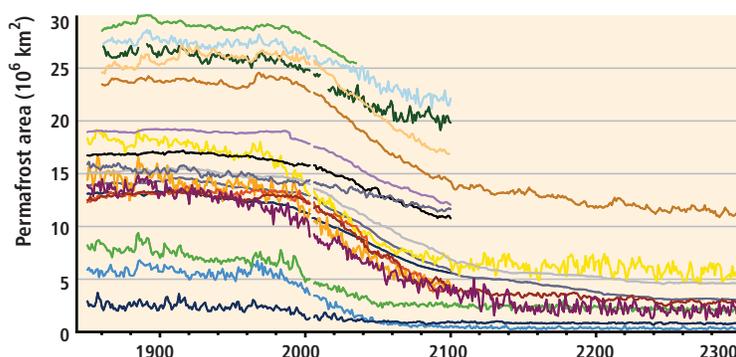
The Arctic tundra biome is experiencing increasing fire disturbance and permafrost degradation. Both of these processes facilitate conditions for woody species establishment in tundra areas, either through incremental migration or via more rapid long-distance dispersal to areas reinitialized by burning (Epstein et al., 2007; Goetz et al., 2011). When already present at the boreal-tundra ecotone, shrub and tree species show increased productivity with warmer conditions (Devi et al., 2008; Andreu-Hayles et al., 2011; Elmendorf et al., 2012). Tundra fires not only emit large quantities of combusted carbon formerly stored in vegetation and organic soils (Mack et al., 2011; Rocha and Shaver, 2011), but also increase active layer depth during summer months (Racine et al., 2004; Liljedahl et al., 2007; Jorgenson et al., 2010), produce landforms associated with thawing of ice-rich permafrost, and can create conditions that alter vegetation succession (Racine et al., 2004; Lantz et al., 2009; Higuera et al., 2011).

It is *virtually certain* that the area of NH permafrost will continue to decline over the first half of the 21st century (see WGI AR5 Chapter 12) in all RCP scenarios (Figure 4-9; Caesar et al., 2013; Koven et al., 2013). In the RCP2.6 scenario of an early stabilization of CO₂ concentrations, the permafrost area is projected to stabilize at a level approximately 20% below the 20th century area, and then begin a slight recovering trend. In RCP4.5, in which CO₂ concentration is stabilized at approximately 550 ppmv by the mid-21st century, the simulations that extend beyond 2100 show permafrost continuing to decline for at least another 250 years. In the RCP8.5 scenario of ongoing CO₂ rise, the permafrost area is simulated to approach zero by the middle of the 22nd century in

(a) RCP2.6 modeled permafrost extent



(b) RCP4.5 modeled permafrost extent



(c) RCP8.5 modeled permafrost extent

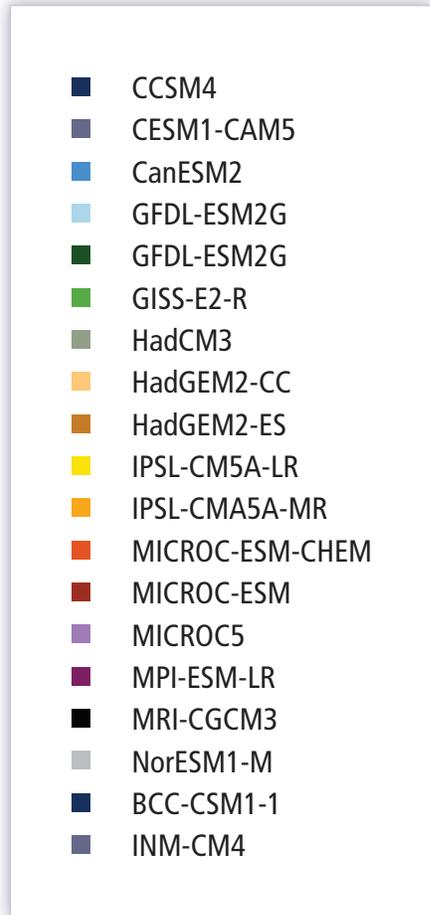
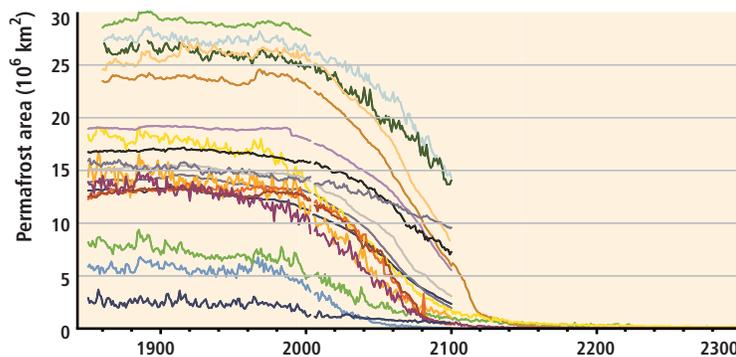


Figure 4-9 | CMIP5 multi-model simulated area of Northern Hemisphere permafrost in the upper 3 m of soil, from 1850 to 2100 or 2300 depending on extent of individual simulations. Each panel shows historical (1850–2005) and projected (2005–2100 or 2300) simulations for (a) Representative Concentration Pathway 2.6 (RCP2.6), (b) RCP4.5, and (c) RCP8.5. The observed current permafrost extent is $15 \times 10^6 \text{ km}^2$. (Based on Koven et al., 2013, with analysis extended to 2300 following Caesar et al., 2013).

simulations that extend beyond 2100. RCP8.5 simulations that ended at 2100 showed continued permafrost decline in the late 21st century, although at slower rates in some cases as the remaining permafrost area decreases (Figure 4-9).

Frozen soils and permafrost currently hold about 1700 PgC, more than twice the carbon than the atmosphere, and thus represent a particularly large vulnerability to climate change (i.e., warming) (see WGI AR5 Chapter 6). Although the Arctic is currently a net carbon sink, continued warming will act to turn the Arctic to a net carbon source, which will in

turn create a potentially strong positive feedback to accelerate Arctic (and global) warming with additional releases of CO_2 , CH_4 , and perhaps N_2O , from the terrestrial biosphere into the atmosphere (*high confidence*; Schuur et al., 2008, 2009; Maslin et al., 2010; McGuire et al., 2010; O’Connor et al., 2010; Schaefer et al., 2011; see WGI AR5 Chapter 6 for detailed treatment of biogeochemistry, including feedbacks). Moreover, this feedback is already accelerating due to climate-induced increases in fire (McGuire et al., 2010; O’Donnell et al., 2011). The rapid retreat of snow cover and resulting spread of shrubs and trees into areas currently dominated by tundra has begun, and will continue to serve

Box 4-4 | Boreal-Tundra Biome Shift

Changes in a suite of ecological processes currently underway across the broader Arctic region are consistent with Earth System Model (ESM) predictions of climate-induced geographic shifts in the range extent and functioning of the tundra and boreal forest biomes (Figure 4-10). Until now, these changes have been gradual shifts across temperature and moisture gradients, rather than abrupt. Responses are expressed through gross and net primary production, microbial respiration, fire and insect disturbance, vegetation composition, species range expansion and contraction, surface energy balance and hydrology, active layer depth and permafrost thaw, and a range of other inter-related variables. Because the high northern latitudes are warming more rapidly than other parts of the Earth, due at least in part to Arctic amplification (Serreze and Francis, 2006), the rate of change in these ecological processes are sufficiently rapid that they can be documented *in situ* (Hinzman et al., 2005; Post et al., 2009; Peng et al., 2011; Elmendorf et al., 2012) as well as from satellite observations (Goetz et al., 2007; Beck, P.S.A. et al., 2011; Xu et al., 2013) and captured in ESMs (McGuire et al., 2010).

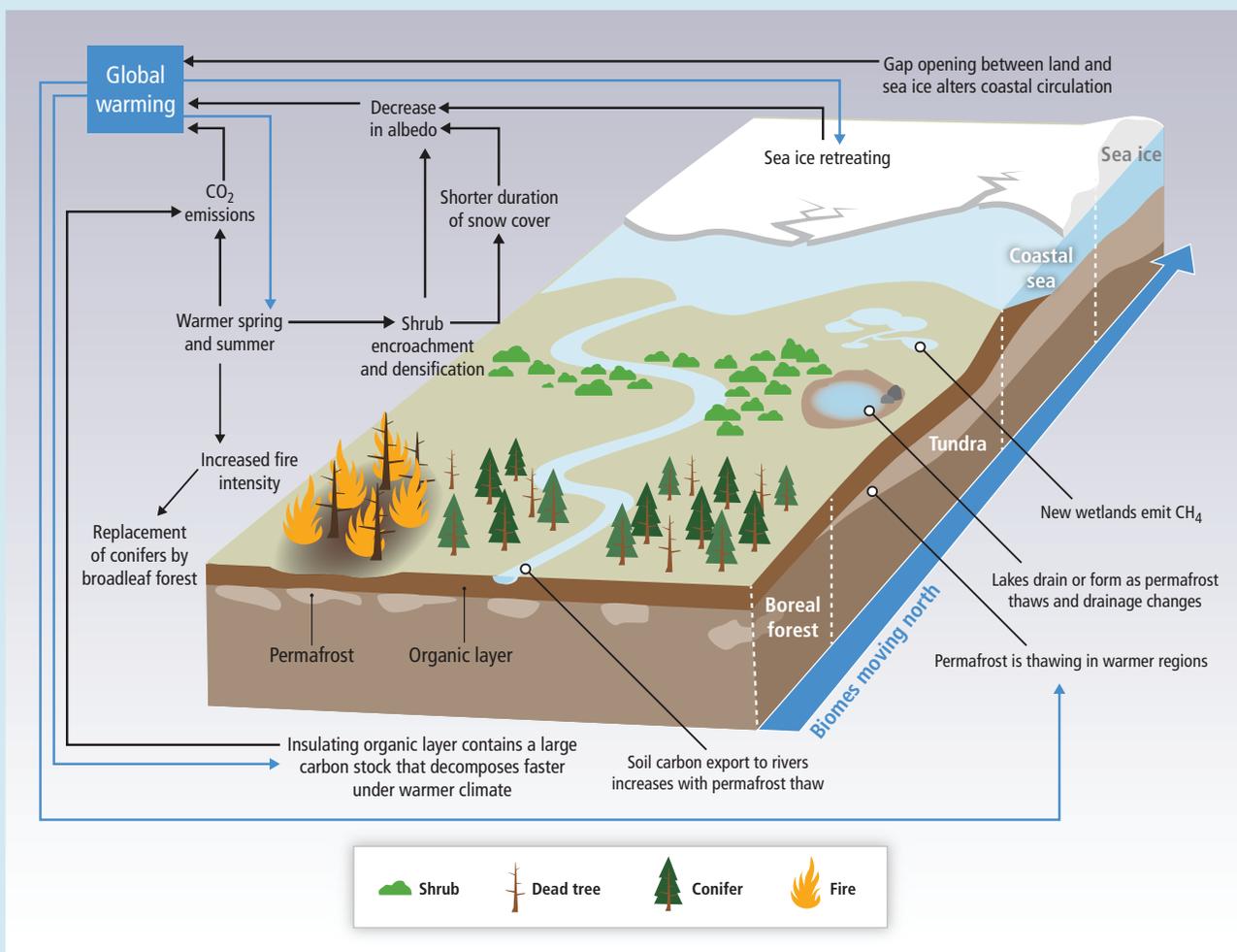


Figure 4-10 | Tundra–boreal biome shift. Earth System Models predict a northward shift of Arctic vegetation with climate warming, as the boreal biome migrates into what is currently tundra. Observations of shrub expansion in tundra, increased tree growth at the tundra–forest transition, and tree mortality 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, permafrost thawing, and methane emissions, with net feedbacks to additional climate change.

Continued next page →

Box 4-4 (continued)

Gradual changes in composition resulting from decreased evergreen conifer productivity and increased mortality, as well as increased deciduous species productivity, can be facilitated by more rapid shifts associated with fire disturbance where it can occur (Mack et al., 2008; Johnstone et al., 2010; Roland et al., 2013). Each of these interacting processes, as well as insect disturbance and associated tree mortality, are tightly coupled with warming-induced drought (Choat et al., 2012; Ma et al., 2012; Anderegg et al., 2013a). Similarly, gradual productivity increases at the boreal-tundra ecotone are facilitated by long distance dispersal into areas disturbed by tundra fire and thermokarsting (Tchebakova et al., 2009; Brown, 2010; Hampe, 2011). 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.

as a positive feedback accelerating high-latitude warming (Chapin III et al., 2005; Bonfils et al., 2012).

There is *medium confidence* that rapid change in the Arctic is affecting its animals. For example, seven of 19 sub-populations of the polar bear are declining in number, while four are stable, one is increasing, and the remaining seven have insufficient data to identify a trend (Vongraven and Richardson, 2011). Declines of two of the sub-populations are linked to reductions in sea ice (Vongraven and Richardson, 2011). Polar bear populations are projected to decline greatly in response to continued Arctic warming (Hunter et al., 2010; Stirling and Derocher, 2012), and it is expected that the populations of other Arctic animals will be affected dramatically by climate change, often in complex but potentially dramatic ways (e.g., Post et al., 2009; Sharma et al., 2009; Gallant et al., 2012; Gilg et al., 2012; Post and Brodie, 2012; Gauthier et al., 2013; Nielsen and Wall, 2013; Prost et al., 2013; White et al., 2013). Simple niche-based or climatic envelope models have difficulty in capturing the full complexity of these future changes (MacDonald, 2010).

There is *high confidence* that alpine systems are already showing a high sensitivity to ongoing climate change and will be highly vulnerable to change in the future. In western North America, warming, glacier retreat, snowpack decline, and drying of soils are already causing a large increase in mountain forest mortality and wildfire, plus other ecosystem impacts (e.g., Westerling et al., 2006; Crimmins et al., 2009; van Mantgem et al., 2009; Pederson et al., 2010; Muhlfeld et al., 2011; Brusca et al., 2013; Williams et al., 2013), and disturbance will continue to be an important agent of climate-induced change in this region (Littell et al., 2010). Globally, tree line altitude appears to be changing, although not always in simple ways (Harsch et al., 2009; Tingley et al., 2012) and may sometimes be due to factors not related to climate change. Responses to climate change in high-altitude ecosystems are taking place in Africa, Asia, Europe, and elsewhere (Cannone et al., 2007, 2008; Yasuda et al., 2007; Lenoir et al., 2008, 2010; Britton et al., 2009; Chen et al., 2009, 2011; Cui and Graf, 2009; Normand et al., 2009; Allen, C.D. et al., 2010; Eggermont et al., 2010; Engler et al., 2011; Kudo et al., 2011; Laurance et al., 2011; Dullinger et al., 2012). For example, in a study of permanent

plots from 1994 to 2004 in the Austrian high Alps, a range contraction of subnival to nival plant species was indicated at the downslope edge, and an expansion of alpine pioneer species at the upslope edge (Pauli et al., 2007). Thermophilous vascular plant species were observed to colonize in alpine mountain-top vegetation across Europe during the past decade (Gottfried et al., 2012). As with the Arctic, permafrost thawing in alpine systems could provide a strong positive feedback (e.g., Tibet; Cui and Graf, 2009).

4.3.3.5. Highly Human-Modified Systems

About a quarter of the land surface is now occupied by ecosystems highly modified by human activities. In this section we assess the vulnerability to climate change only of those modified systems not dealt with elsewhere, that is, excluding agriculture (Chapter 7), freshwater fisheries (Chapter 3), and urban areas (Chapter 8).

4.3.3.5.1. Plantation forestry

Plantation forests are established through afforestation or reforestation, often with tree crop replacement (Dohrenbusch and Bolte, 2007; FAO, 2010). They differ from natural or semi-natural forests (Section 4.3.3.1) by generally being even-aged, having a reduced species diversity (sometimes of non-native species), and being dedicated to the production of timber, pulp, and/or bioenergy. Plantation forests contribute 7% to the global forest area (FAO, 2010), an increase of 5 million hectares between 2000 and 2010 (FAO, 2010). Most recent plantations have been established by afforestation of non-forest areas in the tropics and subtropics and some temperate regions, particularly China (Kirilenko and Sedjo, 2007; FAO, 2010). Afforestation usually results in net CO₂ uptake from the atmosphere (Canadell and Raupach, 2008; Van Minnen et al., 2008) but does not necessarily result in a reduction in global warming (Bala et al., 2007; see Section 4.3.4.5).

Growth rates in plantation forests have generally increased during the last decades but the variability is large. In forests that are not highly

water limited, increased growth is consistent with higher temperatures and extended growing seasons. As in the case of forests in general, clear attribution is difficult because of the interaction of multiple environmental drivers as well as changes in forest management (e.g., Boisvenue and Running, 2006; Ciais et al., 2008; Dale et al., 2010; see also Section 4.3.3.1). In Europe much of the increase has been attributed to recovery following previously more intense harvesting (Ciais et al., 2008; Lindner et al., 2010).

Several studies using forest yield models suggest future increases in forest production (Kirilenko and Sedjo, 2007). These results may overestimate the positive effects of elevated CO₂ (Kirilenko and Sedjo, 2007; see Section 4.2.4.4). The effects of disturbances such as wildfires, forest pests, pathogens, and windstorms, which are major drivers of forest dynamics, are poorly represented in the models (Loustau, 2010; see also Section 4.3.3.1 and Box 4-2). The results from different models often differ substantially both regarding forest productivity (e.g., Sitch et al., 2008; Keenan et al., 2011) and potential species ranges (see Section 4.3.3.1.2). Decreased forest production is expected in already dry forest regions for which further drying is projected, such as the southwestern USA (Williams, A.P. et al., 2010). Extreme drying may also decrease yields in forests currently not water limited (e.g., Sitch et al., 2008; see Section 4.3.3.1). Plantations in cold-limited areas could benefit from global warming, provided that increased fires, storms, pests, and pathogens do not outweigh the potential direct climate effects on tree growth rates.

Low species diversity (and low genetic diversity within species where clones or selected provenances are used) renders plantation forests less resilient to climate change than natural forests (e.g., Hemery, 2008). Choosing provenances that are well adapted to current climates but pre-adapted to future climates is difficult because of uncertainties in climate projections at the time scale of a plantation forest rotation (Broadmeadow et al., 2005). How forest pests and pathogens will spread as a result of climate change and other factors is highly uncertain. New pathogen-tree interactions may arise (e.g., Brasier and Webber, 2010). Adaptive management can decrease the vulnerability of plantation forests to climate change (Hemery, 2008; Bolte et al., 2009; Seppälä, 2009; Dale et al., 2010). For example, risk spreading by promoting mixed stands, containing multiple species or provenances, combined with natural regeneration (Kramer et al., 2010), has been advocated as an adaptation strategy for temperate forests (Hemery, 2008; Bolte et al., 2010) and tropical forests (Erskine et al., 2006; Petit and Montagnini, 2006). Incomplete knowledge of the ecology of tropical tree species and little experience in managing mixed tropical tree plantations remains a problem (Hall et al., 2011). Especially at the equator-ward limits of cold-adapted species, such as Norway spruce (*Picea abies*) in Europe, climate change will *very likely* lead to a shift in the main tree species used for forest plantations (Iverson et al., 2008; Bolte et al., 2010).

4.3.3.5.2. Bioenergy systems

The production of modern bioenergy is growing rapidly throughout the world in response to climate mitigation and energy security policies (Kirilenko and Sedjo, 2007). WGIII AR5 Chapter 7 addresses the potential of bioenergy as a climate mitigation strategy. The vulnerability of

bioenergy systems to climate change is similar to that of plantation forestry (Section 4.3.3.5.1) or food crops (Section 7.3): in summary, they remain viable in the future in most but not all locations, but their viability is increasingly uncertain for high levels of climate change (Haberl et al., 2011). Oliver, R.J. et al. (2009) suggested that rising CO₂ might contribute to increased drought tolerance in bioenergy crops (because it leads to improved plant water use efficiency).

The unintended consequences of large-scale land use changes driven by increasing bioenergy demand are addressed in Section 4.4.4.

4.3.3.5.3. Cultural landscapes

Cultural landscapes are characterized by a long history of human-nature interactions, which results in a particular configuration of species and landscape pattern attaining high cultural significance (Rössler, 2006). Examples are grassland or mixed agriculture landscapes in Europe, rice landscapes in Asia (Kuldna et al., 2009), and many others across the globe (e.g., Rössler, 2006; Heckenberger et al., 2007). Such landscapes are often agricultural, but we deal with them here because their perceived value is only partly in terms of their agricultural products.

It has been suggested that protected area networks (such as Natura 2000 in Europe, which includes many cultural landscape elements) be adjusted to take into account climate change (Bertzky et al., 2010). Conserving species in cultural landscapes (e.g., EU Council, 1992) generally depends on maintaining certain types of land use. Doing so under climate change requires profound knowledge of the systems and species involved, and conservation success so far has been limited (see Thomas et al., 2009, for a notable exception). Understanding the relative importance of climate change and land management change is critical (Settele and Kühn, 2009). To date land use changes have been the most obvious driver of change (Nowicki et al., 2007); impacts have been attributed to climate change (with *low to medium confidence*) in only a few examples (Devictor et al., 2012). Even in these, combined land use-climate effects explain the pattern of observed threats better than either alone (Schweiger et al., 2008, 2012; Clavero et al., 2011).

There is *very high confidence* that species composition and landscape structure are changing in cultural landscapes such as Satoyama landscapes in Japan or mixed forest, agricultural landscapes in Europe. Models and experiments suggest that climate change should be contributing to these observed changes. The land use and land management signal is so strong in these landscapes that there is *very low confidence* that we can attribute these observations to climate change (Figure 4-4).

4.3.3.5.4. Urban ecosystems

Although urban areas (for definition see Section 8.1.2) cover only 0.5% of the Earth's land surface (Schneider et al., 2009), more than half of humanity lives there (increasing annually by 74 million people; UN DESA Population Division, 2012) and they harbor a large variety of species (McKinney, 2008). The frequency and magnitude of warm days and nights (heat waves) is *virtually certain* to increase globally in the future

Frequently Asked Questions

FAQ 4.5 | Why does it matter if ecosystems are altered by climate change?

Ecosystems provide essential services for all life: food, life-supporting atmospheric conditions, drinkable water, as well as raw materials for basic human needs such as clothing and housing. Ecosystems play a critical role in limiting the spread of human and non-human diseases. They have a strong impact on the weather and climate itself, which in turn impacts agriculture, food supplies, socioeconomic conditions, floods, and physical infrastructure. When ecosystems change, their capacity to supply these services changes as well—for better or worse. Human well-being is put at risk, along with the welfare of millions of other species. People have a strong emotional, spiritual, and ethical attachment to the ecosystems they know, and the species they contain.

By “ecosystem change” we mean changes in some or all of the following: the number and types of organisms present; the ecosystem’s physical appearance (e.g., tall or short, open or dense vegetation); and the functioning of the system and all its interactive parts, including the cycling of nutrients and productivity. Though in the long term not all ecosystem changes are detrimental to all people or to all species, the faster and further ecosystems change in response to new climatic conditions, the more challenging it is for humans and other species to adapt to the new conditions.

(IPCC, 2012); this trend is higher in urban than in rural areas (McCarthy et al., 2010). Heavy rainfall events are also projected to increase (IPCC, 2012), and although the hydrological conditions in urban areas make them prone to flooding (*medium confidence*), there is *limited evidence* that they will be over-proportionally affected. It is very likely that sea level rise in the future will contribute to flooding, erosion, and salinization of coastal urban ecosystems (IPCC, 2012). Climate change is projected to increase the frequency of landslides (UN-HABITAT, 2011). Climate change impacts on urban ecosystems and biodiversity have received comparatively little attention, with water availability being an exception (Hunt and Watkiss, 2011). Changes in water availability and quality due to changes in precipitation, evaporation, or in salinity regimes will especially affect urban freshwater ecosystems (Hunt and Watkiss, 2011). As in other ecosystems, climate change will lead to a change in species composition, the frequency of traits, and ecosystem services from urban ecosystems. Knapp, S. et al. (2008) found that trait composition of plant communities changes during urbanization toward adaptive characteristics of dry and warm environments (see also Sections 4.2.4.6 and 4.3.2.5). Urban areas are one of the main points of introduction of alien species (e.g., for plants through urban gardening; Knapp, S. et al., 2012). Increased damage by phytophagous insects to plants in urban environments is anticipated (Kollár et al., 2009; Lopez-Vaamonde et al., 2010; Tubby and Webber, 2010; see also Section 8.2.4.5).

4.3.4. Impacts on Key Ecosystem Services

Ecosystem services are the benefits that people derive from ecosystems (see Glossary). Many ecosystem services are plausibly vulnerable to climate change. The Millennium Ecosystem Assessment classification (Millennium Ecosystem Assessment, 2003) recognizes *provisioning services* such as food (Chapter 7), fiber (Section 4.3.4.2), bioenergy (Section 4.3.4.3), and water (Chapter 3); *regulating services* such as climate regulation (Section 4.3.4.5), pollination, pest and disease control (Section 4.3.4.4), and flood control (Chapter 3); *supporting services* such

as primary production (Section 4.3.2.2) and nutrient cycling (Section 4.2.4.2, and indirectly Section 4.3.2.3); and *cultural services*, including recreation and aesthetic and spiritual benefits (Section 10.6). Section 4.3.4.1 focuses on ecosystem services not already covered in the sections referenced above.

4.3.4.1. Habitat for Biodiversity

Climate change can alter habitat for species by inducing (1) shifts in habitat distribution that are not followed by species, (2) shifts in species distributions that move them outside of their preferred habitats, and (3) changes in habitat quality (Dullinger et al., 2012; Urban et al., 2012). Climate change impacts on habitats for biodiversity are already occurring (see the polar bear example in Section 28.2.2.1.3) but are not yet a widespread phenomenon. Models of future climate change-induced shifts in the distribution of ecosystems suggest that many species could be outside of their preferred habitats within the next few decades (Urban et al., 2012; see Sections 4.3.2.5, 4.3.3, and Figure 4-1).

Hole et al. (2009) report that the majority of African birds would have to move large distances (up to several hundred kilometers) over the next 60 years (under SRES B2a), resulting in substantial turnover of species within protected areas (>50% turnover in more than 40% of Important Bird Areas of Africa). To reach suitable climates they will have to migrate across unfavorable habitats. Many may continue to find suitable climate within the protected area network, but will be forced to cope with new habitat constraints (Hole et al., 2009). Araujo et al. (2011) estimate that by 2080 approximately 60% ($58 \pm 2.6\%$) of plants and vertebrate species will no longer have favorable climates within European protected areas, often pushing them into unsuitable or less preferred habitats (based on SRES A1, A2, B1, and A1FI scenarios). Wiens et al. (2011) project similar effects in the western USA (until the year 2069, based on SRES A2 scenarios), but also find that climate change may open up new opportunities for protecting species in areas where

climate is currently unsuitable. In some cases climate change may allow species to move into areas of lower current or future land use pressure including protected areas (Bomhard et al., 2005). These studies strongly argue for a rethinking of protected areas networks and of the importance of the habitat matrix outside of protected areas as a key to migration and long-term survival of species (see Sections 4.4.2.2, 4.4.2.3).

In the long term, some habitat types may disappear entirely due to climate change (see Section 4.3.3 and Figure 4-1). Climates are projected to occur in the future that at least in some features do not represent climates that existed in the past (Williams, J.W. et al., 2007; Wiens et al., 2011), and in the past climate shifts have resulted in vegetation types that have no current analog (Section 4.2.3). The impacts of habitat change on species abundance and extinction risk are difficult to evaluate because at least some species are able to adapt to novel habitats (Prugh et al., 2008; Oliver, T. et al., 2009). The uncertainty in habitat specificity is one reason why quantitative projection of changes in extinction rates is difficult (Malcolm et al., 2006).

The effects of climate change on habitat quality are less well studied than shifts in species or habitat distributions. Several recent studies indicate that climate change may have altered habitat quality already and will continue to do so (Iverson et al., 2011; Matthews et al., 2011). For example, decreasing snowfall in the southwestern USA has negatively affected the habitat for songbirds (Martin and Maron, 2012).

4.3.4.2. Timber and Pulp Production

In most areas with forest plantations, forest growth rates have increased during the last decades, but the variability is large, and in some areas production has decreased (see Section 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 Section 4.3.3.1). In Europe a reduction in harvesting intensity has contributed (Ciais et al., 2008; Lindner et al., 2010).

Forest yield models project future increases in forest production under climate change, perhaps over optimistically (Kirilenko and Sedjo, 2007; see Section 4.2.4.4). Using a model that accounts for fire effects and insect damage, Kurz et al. (2008) showed that the Canadian forest sector may have transitioned from a sink to a source of carbon.

4.3.4.3. Biomass-Derived Energy

Bioenergy sources include traditional forms such as wood and charcoal from forests (see Section 4.3.3.1) and more modern forms such as the industrial burning of biomass wastes, the production of ethanol and biodiesel, and plantations of bioenergy crops. While traditional biofuels have been in general decline as users switch to fossil fuels or electricity, they remain dominant energy sources in many less developed parts of the world, such as Africa, and retain a niche in developed countries.

Generally, potentials of bioenergy production under climate change may be high, but are very uncertain (Haberl et al., 2011).

4.3.4.4. Pollination, Pest, and Disease Regulation

It can be inferred that global change will result in new communities (Gilman et al., 2010; Schweiger et al., 2010). As these will have had little opportunity for coevolution, changes in ecological interactions, such as shifts in herbivore diets, the range of prey of predators, or in pollination networks are to be expected (Tylianakis et al., 2008; Schweiger et al., 2012). This may result in temporarily reduced effectiveness of the “regulating services,” which generally depend on species interactions (Montoya and Raffaelli, 2010). Burkle et al. (2013) show that the loss of species reduces co-occurrence of interacting species and thus reduces ecosystem functions based on them.

Climate change tends to increase the abundance of pest species, particularly in previously cooler climates, but assessments of changes in impacts are hard to make (Payette, 2007). Insect pests are directly influenced by climate change, for example, through a longer warm season during which to breed, and indirectly, for example, through the quality of food plants (Jamieson et al., 2012) or via changes in their natural enemies (predators and parasitoids). Insects have well-defined temperature optima; warming toward the optimum leads to increased vitality and reproduction (Allen, C.D. et al., 2010). Mild winters in temperate areas promote pests formerly controlled by frost sensitivity. For the vast majority of indirect effects, information is scarce. Further assessments of climate change effects on pest and disease dynamics are found in Sections 7.3.2.3 for agricultural pests and 11.5.1 for human diseases.

Climate change has severe negative impacts on pollinators (including honeybees) and pollination (Kjøl et al., 2011) (*medium confidence*). After land use changes, climate change is regarded as the second most relevant factor responsible for the decline of pollinators (Potts et al., 2010; for other factors see Biesmeijer et al., 2006; Brittain et al., 2010a,b). The potential influence of climate change on pollination can be manifold (compare Hegland et al., 2009; Schweiger et al., 2010; Roberts et al., 2011). There are a few observational studies, which mostly relate to the phenological decoupling of plants and their pollinators (Gordo and Sanz, 2005; Bartomeus et al., 2011). While Willmer (2012) states, based on experimental studies, that phenological effects may be less important than has been suggested, an analysis of phenological observations in plants by Wolkovich et al. (2012) shows that experimental data on phenology may grossly underestimate the actual phenological shifts.

Le Conte and Navajas (2008) state that the generally observed decline in honeybees is a clear indication of an increasing susceptibility to global change phenomena, with pesticide application, new diseases, and stress (and a combination of these) as the most relevant causes. Climate change may contribute by modifying the balance between honeybees and their environment (including exposure or susceptibility to diseases). Honeybees show a high capacity to adjust to a variety of environments; their high genetic diversity should allow them to also cope with climatic change (Bartomeus et al., 2011). The preservation of

genetic variability within honeybees is regarded as a key adaptation strategy for pollination services (Le Conte and Navajas, 2008).

4.3.4.5. Moderation of Climate Change, Variability, and Extremes

The focus of this section is on processes operating at regional to global scales, rather than the well-known microclimatic benefits of ecosystems in smoothing day-night temperature variations and providing local evaporative cooling. In the decade 2000–2009, the global net uptake of CO₂ by terrestrial ecosystems was a large fraction of the anthropogenic CO₂ emissions to the atmosphere from all sources, reducing the rate of climate change proportionately (Section 4.3.2.3; WGI AR5 Section 6.3.2).

Afforestation or reforestation are potential climate mitigation options (Van Minnen et al., 2008; Vaughan and Lenton, 2011; Fiorese and Guariso, 2013; Singh et al., 2013) but, as discussed in Section 4.2.4.1, the net effect of afforestation on the global climate is mixed and context dependent. Wickham et al. (2012) found significant positive correlations between the average annual surface temperature and the proportion of forest in the landscape and conclude that the climate benefit of temperate afforestation is unclear. Where low-albedo forest canopies replace higher-albedo surfaces such as soil, grassland, or snow, the resultant increase in net radiative forcing counteracts the benefits of carbon sequestration to some degree (Arora and Montenegro, 2011). Where the cloud cover fraction is low and the albedo difference is large, that is, outside the humid tropics, the long-term net result of afforestation can be global warming (Bala et al., 2007; Bathiany et al., 2010; Schwaiger and Bird, 2010). Accounting for changes in albedo and indirect greenhouse effects are not currently required in the formal rules for quantifying for the climate effects of land use activities (Schwaiger and Bird, 2010; Kirschbaum et al., 2012). There are potential negative trade-offs between afforestation for climate mitigation purposes and other ecosystem services, such as water supply (Jackson et al., 2005) and biodiversity maintenance (CBD, 2012; Russell et al., 2012).

It has been suggested (Ridgwell et al., 2009) that planting large areas of crop varieties with highly reflective leaves could help mitigate global change. Model analyses indicate this “geo-engineering” strategy would be marginally effective at high latitudes, but have undesirable climate consequences at low latitudes. Measurements of leaf albedo in major crops show that the current range of variability is insufficient to make a meaningful difference to the global climate (Doughty et al., 2011).

4.4. Adaptation and Its Limits

4.4.1. Autonomous Adaptation by Ecosystems and Wild Organisms

Autonomous adaptation (see Glossary under adaptation) refers to the adjustments made by ecosystems, including their human components, without external intervention, in response to a changing environment (Smit et al., 2000)—also called “spontaneous adaptation” (Smit et al., 2007). In the context of human systems it is sometimes called “coping capacity.” The capacity for autonomous adaptation is part of resilience but is not exactly synonymous (Walker et al., 2004).

All social and ecological systems have some capacity for autonomous adaptation. Ecosystems that have persisted for a long time can reasonably be inferred to have a high capacity for autonomous adaptation, at least with respect to the variability that they have experienced in the past. An environmental change that is more rapid than in the past or is accompanied by other stresses may exceed the previously demonstrated adaptive capacity of the system. Adaptation at one level, for instance by organisms in a community, can confer greater resilience at higher organization levels, such as the ecosystem (Morecroft et al., 2012). The mechanisms of autonomous adaptation of organisms and ecosystems consist of changes in the physiology, behavior, phenology, or physical form of organisms, within the range permitted by their genes and the variety of genes in the population; changes in the genetic composition of the populations; and change in the composition of the community, through in- or out-migration or local extinction.

The ability to project impacts of climate change on ecosystems is complicated by the potential for species to adapt. Adaptation by individual species increases their ability to survive and flourish under different climatic conditions, possibly leading to lower risks of extinction than predicted from statistical correlations between current distribution and climate (Botkin et al., 2007). It may also affect their interactions with other species, leading to disruption of the biotic community (Visser and Both, 2005).

4.4.1.1. Phenological

Changes in phenology are occurring in many species and locations (Section 4.3.2.1). Further evidence since AR4 shows how this can be an adaptation to climate change, but also the limits to phenological adaptation. An organism’s phenology is typically highly adapted to the climate seasonality of the environment in which it evolved. Species unable to adjust their phenological behavior will be negatively affected, particularly in highly seasonal habitats (Both et al., 2010).

Moreover, the phenology of any species also needs to be keyed to the phenology of other species with which it interacts, such as competitors, food species, and pollinators. Systematic cross-taxa studies indicate different rates of phenological change for different species and trophic levels (Parmesan, 2007; Cook et al., 2008; Thackeray et al., 2010). If adaptation is insufficiently rapid or coordinated between interdependent species, disruption of ecological features such as trophic cascades, competitive hierarchies, and species coexistence is inferred to result (Nakazawa and Doi, 2012). Lack of coordination can occur if one of the species is cued to environmental signals that are not affected by climate change, such as day length (Parmesan, 2006). Increasing temperatures may bring species either more into or out of synchrony, depending on their respective starting positions (Singer and Parmesan, 2010), although evidence is more toward a loss of synchrony (Thackeray et al., 2010).

Changes in interspecific interactions, such as predator-prey or interspecific competition for food, stemming from changes in phenological characteristics and breakdown in synchrony between species have been observed. For example, bird breeding is most effective when synchronized with the availability of food, so changes in the phenology of food supplies can exert a selective pressure on birds. In a study of 100

European migratory bird species, those that advanced their arrival date showed stable or increasing populations between 1990 and 2000, while those that did not adjust their arrival date on average showed declining populations (Møller et al., 2008). In a comparison of nine Dutch populations of the migratory pied flycatcher (*Ficedula hypoleuca*) between 1987 and 2003, populations declined by 90% in areas where food peaked early in the season and the arrival of the birds was mis-timed, but not in areas with a later food peak that could still be exploited by early breeding birds (Both et al., 2006). However, compensating processes can exist: for example, in a 4-decade study of great tits (*Parus major*), breeding populations were buffered against phenological mismatch due to relaxed competition between individual fledglings (Reed et al., 2013). Between 1970 and 1990, changes in migration date did not predict changes in population sizes (Møller et al., 2008).

Bird breeding can also be affected by phenological shifts in competing species and predators. Between 1953 and 2005 in southwestern Finland, the onset of breeding of the resident great tit *Parus major* and the migratory pied flycatcher (*Ficedula hypoleuca*) became closer to each other, increasing competition between them (Ahola et al., 2007). The edible dormouse (*Glis glis*), a nest predator, advanced its hibernation termination by -8 days per decade in the Czech Republic between 1980 and 2005 due to increasing annual spring air temperatures, leading to increased nest predation in three out of four surveyed bird species (Adamik and Kral, 2008).

Plant-insect interactions have also been observed to change. In Illinois, USA, the pattern of which plants were pollinated by which bees were altered by differing rates of phenological shifts and landscape changes over 120 years, with 50% of bee species becoming locally extinct (Burkle et al., 2013). Increasing asynchrony of the winter moth (*Operophtera brumata*) and its feeding host oak tree (*Quercus robur*) in the Netherlands was linked to increasing spring temperatures but unchanging winter temperatures (van Asch and Visser, 2007). Warmer temperatures shorten the development period of European pine sawfly larvae (*Neodiprion sertifer*), reducing the risk of predation and potentially increasing the risk of insect outbreaks, but interactions with other factors including day length and food quality may complicate this prediction (Kollberg et al., 2013). In North America, the spruce budworm (*Choristaneura fumiferana*) lays eggs with a wide range of emergence timings, so the population as a whole is less sensitive to changing phenology of host trees (Volney and Fleming, 2007).

The environmental cues for phenological events are complex and multi-layered (Körner and Basler, 2010; Singer and Parmesan, 2010). For instance, many late-succession temperate trees require a chilling period in winter, followed by a threshold in day length, and only then are sensitive to temperature. As a result, simple projections of current phenological trends may be misleading, since the relative importance of cues can change (Cook et al., 2012b). The effects are complex and sometimes apparently counterintuitive, such as the increased sensitivity of flowering in high-altitude perennial herbs in the Rocky Mountains to frost because plants begin flowering earlier as a result of earlier snowmelt (Inouye, 2008).

It has been suggested that shorter generation times give greater opportunity for autonomous adaptation through natural selection

(Rosenheim and Tabashnik, 1991; Bertaux et al., 2004), but a standardized assessment of 25,532 rates of phenological change for 726 UK taxa indicated that generation time had only limited influence on adaptation rates (Thackeray et al., 2010).

There is *high confidence (much evidence, medium agreement)* that climate change-induced phenological shifts will continue to alter the interactions between species in regions with a marked seasonal cycle.

4.4.1.2. Evolutionary and Genetic

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

4.4.1.2.1. Observed evolutionary and genetic responses to rapid changes in climate

There is a small but growing body of observations supporting the AR4 assessment that some species may have adapted to recent climate warming or to climatic extremes through genetic responses (e.g., plants: Franks and Weis, 2008; Hill et al., 2011; Anderson et al., 2012b; vertebrates: Ozgul et al., 2010; Phillimore et al., 2010; Husby et al., 2011; Karell et al., 2011; insects: Buckley et al., 2012; van Asch et al., 2012). Karell et al. (2011) found increasing numbers of brown genotypes of the tawny owl (*Strix aluco*) in Finland over the course of the last 28 years and attributed it to fewer snow-rich winters, which creates strong selection pressure against the white genotype. Earlier spawning by the common frog (*Rana temporaria*) in Britain could be attributed largely to local genetic adaptation to increasing spring temperatures (Phillimore et al., 2010). Using a combination of models and observations, Husby et al. (2011) have built a case for detection and attribution of genetic adaptation in an insectivorous bird and in an herbivorous insect that has tracked warming-related changes in the budburst timing of its host tree (van Asch et al., 2012). In contrast, many species appear to be maladapted to changing climates, in part because factors such as limited existing genetic variation, weak heritability of adaptive traits, or conflicting constraints on adaptation create low potential for rapid evolution (Knudsen et al., 2011; Ketola et al., 2012; Merilä, 2012; Mihoub et al., 2012). Most studies of rapid evolution suffer from methodological

weaknesses, making it difficult to demonstrate clearly a genetic basis underlying observed phenotypic responses to environmental change (Gienapp et al., 2008; Franks and Hoffmann, 2012; Hansen et al., 2012; Merilä, 2012). Rapid advances in quantitative genetics, genomics, and phylogenetics, combined with recent progress on conceptual frameworks, will substantially improve the detection and attribution of genetic responses to changing climate over the next few years (Davis, C.C. et al., 2010; Salamin et al., 2010; Hoffmann and Sgro, 2011). In sum, there are few observational studies of rapid evolution and difficulties in detection and attribution, so there is only *medium confidence* that some species have responded to recent changes in climate through genetic adaptations, and insufficient evidence to determine if this is a widespread phenomenon (thus *low confidence* for detection and attribution across all species; Figure 4-4).

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

4.4.1.2.2. Mechanisms mediating rapid evolutionary response to future climate change

Studies of genetic variability across species ranges, and models that couple gene flow with spatially explicit population dynamics, suggest counterintuitive responses to climate change. Too much or too little gene flow to populations at range margins can create fragile, maladapted populations, which is in contrast to the current wisdom that populations at the range margins may be best adapted to global warming (Bridle et al., 2010; Hill et al., 2011). Conversely, there is evidence from experiments, models, and observations that populations in the center of species ranges may in some cases be more sensitive to environmental change than those at range boundaries (Bell and Gonzalez, 2009). Generalization is complicated by the interactions between local adaptation, gene flow, population dynamics, and species interactions (Bridle et al., 2010; Norberg et al., 2012).

Substantial progress has been made since AR4 in developing models for exploring whether genetic adaptation is fast enough to track climate

change. Models of long-lived tree species suggest that existing genetic variation may be sufficient to slightly attenuate negative impacts of future climate change (Kuparinen et al., 2010; Kremer et al., 2012). However, these studies also indicate that adaptive responses will lag far behind even modest rates of projected climate change, owing to the very long generation time of trees. In a species with much shorter generation times, the great tit (*Parus major*), Gienapp et al. (2013) found that modeled avian breeding times tracked climate change, only at low to moderate rates of change. For a herbivorous insect with an even faster life cycle, van Asch et al. (2007, 2012) predicted that rapid evolution of the phenological response should have allowed it to track recent warming, which it has.

More broadly, models suggest that species with short generation times (1 year or less) potentially have the capacity to genetically adapt to even the most rapid rates of projected climate change given large enough present-day populations, but species with longer generation times or small populations could be at risk of extinction at moderate to high rates of climate change (Walters et al., 2012; Vedder et al., 2013). Recent experimental and theoretical work on “evolutionary rescue” shows that long-term avoidance of extinction through genetic adaptation to hostile environments is possible, but requires large initial genetic variation and population sizes and is accompanied by substantial loss of genetic diversity, reductions in population size, and range contractions over many generations before population recovery (Bell, 2013; Schiffrers et al., 2013).

Model-based projections must be viewed with considerable caution because there are many evolutionary and ecological mechanisms not accounted for in most models that can either speed up or inhibit heritable adaptation to climate change (Cobben et al., 2012; Norberg et al., 2012; Kovach-Orr and Fussmann, 2013). In some cases, accounting for evolutionary processes in models even leads to predictions of greater maladaptation to climate change, resulting in rapid population declines (Hendry and Gonzalez, 2008; Ferriere and Legendre, 2013). Phenotypic plasticity is thought to generally improve the odds of adaptation to climate change. High plasticity in the face of climate change that has low fitness costs can greatly improve the odds of adaptation; however, plasticity with high costs leads to only modest amounts of adaptation (Chevin et al., 2010).

AR4 concluded that “projected rates of climate change are *very likely* to exceed rates of evolutionary adaptation in many species (*high confidence*)” (Fischlin et al., 2007). Work since then provides a similar, but more nuanced view of rapid evolution in the face of future climate change. The lack of adaptation in some species to recent changes in climate, broad support for niche conservatism, and models showing limited adaptive capacity in species with long generation times all indicate that high rates of climate change (RCP8.5) will exceed the adaptive capacities of many species (*high confidence*). On the other hand, evidence from observations and models also indicates that there is substantial capacity for genetic adaptation to attenuate phenological shifts, population declines, and local extinctions in many species, especially for low rates of climate change (RCP2.6) (*high confidence*). Projected adaptation to climate change is frequently characterized by population declines and loss of genetic diversity for many generations (*medium confidence*), thereby increasing species vulnerability to other pressures.

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 observed 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 4-5). Second, the ecosystem interactions can remain intact only if all parts of the ecosystem migrate simultaneously and at the same rate. Third, the contemporary landscape and inland water systems contain many barriers to migration, in the form of habitat fragmentation, roads, human settlements, and dams. Mountain ecosystems are less constrained by these factors than flat-land ecosystems, but have additional impediments for species already close to the top of the mountain.

4.4.2. Human-Assisted Adaptation

Human-assisted adaptation means a deliberate intervention with the intent of increasing the capacity of the target organism, ecosystem, or socio-ecological system to survive and function at an acceptable level in the presence of climate change. It is also known as “planned adaptation” (Smit et al., 2007). This chapter focuses less on the adaptation of people, human communities, and infrastructure, as they are the topics of Chapters 8 to 17, and more on non-human organisms and ecosystems, while acknowledging the importance of the human elements within the ecosystem. Intervention in this context means a range of actions, including ensuring the presence of suitable habitat and dispersal pathways; reducing non-climate stressors; and physically moving organisms and storing and establishing them in new places. In addition to the other approaches assessed in this section, “Ecosystem-Based Adaptation” (see Box CC-EA) 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. Note that there are risks associated with all forms of human-assisted adaptation (see Section 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, as 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). Protective and restorative actions aimed at increasing resilience can also be a cost-effective means as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change and may have other social, economic, and cultural benefits. This is part of “ecosystem-based adaptation” (Colls et al., 2009; Box CC-EA).

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 most biodiversity exists outside rather than in protected areas and this between-protected area matrix is as important; that it is usually 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 (Thomas et al., 2012).

Hickler et al. (2012) analyzed the layout of protected areas in Europe and concluded that under projected 21st century climate change a third to a half of them would potentially be occupied by different vegetation than they currently represent. The new areas that need to be added to the existing protected area network to ensure future representativeness is situation specific, but some general design rules apply: orientation along climate gradients (e.g., altitudinal gradients) is more effective than orientation across them (Roux et al., 2008); regional scale planning is more effective than treating each local case independently because it is the network of habitats and protected areas that confers resilience rather than any single element (Heller and Zavaleta, 2009); and better integration of protected areas with a biodiversity-hospitable landscape outside is more effective than treating the protected areas as islands (Willis and Bhagwat, 2009). Dunlop et al. (2012) assessed the implications of climate change for biodiversity conservation in Australia and found many opportunities to facilitate the natural adaptation of biodiversity, including expanding the network of protected areas and restoring habitat at a large scale.

4.4.2.3. Landscape and Watershed Management

The need to include climate change into the management of vulnerable ecosystems is explicitly included in the strategic goals of the Convention on Biological Diversity. Oliver et al. (2012b) developed decision trees based on three scenarios: (1) *adversely sensitive*, where areas within the species current geographical range will become climatically unsuitable with a changing climate; (2) *climate overlap*, where there are areas that should remain climatically suitable within the species' range; and (3) *new climatic space*, which refers to areas outside of the current range that are projected to become suitable. Heller and Zavaleta (2009) reviewed recommendations in the published literature and argue that the majority of them, such as increase habitat heterogeneity of sites and connectivity of habitats across landscapes, lack sufficient specificity to ensure the persistence of many species and related ecosystem services to ongoing climate change. To date, recommendations are overwhelmingly focused on ecological data, neglecting social science insights. Few resources or capacity exist to guide adaptation planning processes at any scale.

Frequently Asked Questions

FAQ 4.6 | Can ecosystems be managed to help them and people to adapt to climate change?

The ability of human societies to adapt to climate change will depend, in large measure, on the management of terrestrial and inland freshwater ecosystems. A fifth of global human-caused carbon emissions today are absorbed by terrestrial ecosystems; this important carbon sink operates largely without human intervention, but could be increased through a concerted effort to reduce forest loss and to restore damaged ecosystems, which also co-benefits the conservation of biodiversity.

The clearing and degradation of forests and peatlands represents a source of carbon emissions to the atmosphere which can be reduced through management; for instance, there has been a three-quarters decline in the rate of deforestation in the Brazilian Amazon in the last 2 decades. Adaptation is also helped through more proactive detection and management of wildfire and pest outbreaks, reduced drainage of peatlands, the creation of species migration corridors, and assisted migration.

Climate-induced impacts to hydrological and thermal regimes in freshwater systems can be offset through improved management of environmental flow releases from reservoirs (Arthington et al., 2006, 2010 and references therein; Poff et al., 2010). Protection and restoration of riparian vegetation in small stream systems provide an effective strategy to moderate temperature regimes and offset warming, and protect water quality for downstream ecosystems and water supply areas (Davies, 2010; Capon et al., 2013).

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

Steenberg et al. (2011) simulated the effect on adaptive capacity of three variables related to timber harvesting: the canopy-opening size of harvests, the age of harvested trees within a stand, and the species composition of harvested trees within a stand. The combination of all three adaptation treatments allowed target species and old forest to remain reasonably well represented without diminishing the timber supply. This minimized the trade-offs between management values and climate adaptation objectives. Manipulation of vegetation composition and stand structure has been proposed as a strategy for offsetting climatic change impacts on wildfires in Canada. Large areas of boreal forests are currently being harvested and there may be opportunities for using planned manipulation of vegetation for management of future wildfire risks. This management option could also provide an additional

benefit to the use of assisted species migration because the latter would require introducing non-flammable broadleaves species into forests that are otherwise highly flammable (Girardin et al., 2013b; Terrier et al., 2013). Harvesting practices, such as partial cuts that limit the opening of the forest cover created by harvest, will be a key element to maintain diverse forest compositions and age class distributions in boreal forests. Another sound option for decreasing the exposure of silvicultural investments to an increasing fire danger is to use tree species requiring a shorter rotation (Girardin et al., 2013a).

4.4.2.4. Assisted Migration

Assisted migration has been proposed when fragmentation of habitats limits migration potential or when natural migration rates are outstripped by the pace of climate change (Hoegh-Guldberg et al., 2008; Vitt et al., 2010; Chmura et al., 2011; Loss et al., 2011; Ste-Marie et al., 2011). The options for management can be summarized as: (1) try to maintain or improve existing habitat or environment so that species do not have to move (e.g., Settele and Kühn, 2009); (2) maintain or improve migration corridors, including active management to improve survival along the moving margin of the distribution (Lawson et al., 2012); and (3) directly translocate species or genetically distinct populations within a species (Aitken et al., 2008; Hoegh-Guldberg et al., 2008; Rehfeldt and Jaquish, 2010; Loss et al., 2011; Pedlar et al., 2012). There is *low agreement* whether it is better to increase the resilience to climate change of ecosystems as they currently occur, or to enhance capacity of ecosystems to transform in the face of climate change (Richardson et al., 2009).

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

species, may decrease species diversity, and may also facilitate the spread of invasive species (Cadotte, 2006; Brisson et al., 2010; Matthiessen et al., 2010).

There is *medium agreement* that the practice of assisted migration of targeted species is a useful adaptation option (Hoegh-Guldberg et al., 2008; Vitt et al., 2009; Willis and Bhagwat, 2009; Loss et al., 2011; Hewitt et al., 2011). The velocity of 21st century climate change and substantial habitat fragmentation in large parts of the world means that many species will be unable to migrate or adapt fast enough to keep pace with climate change (Figure 4-5), posing problems for long-term survival of the species. Some ecologists believe that careful selection of species to be moved would minimize the risk of undesirable impacts on existing communities or ecosystem function (Minteer and Collins, 2010), but others argue that the history of intentional species introductions shows that the outcomes are unpredictable and in many cases have had disastrous impacts (Ricciardi and Simberloff, 2009). The number of species that require assisted migration could easily overwhelm funding capacity (Minteer and Collins, 2010). Decisions regarding which species should be translocated are complex and debatable, given variability among and within species and the ethical issues involved (Aubin et al., 2011; Winder, R. et al., 2011).

4.4.2.5. *Ex Situ* Conservation

Conservation of plant and animal genetic resources outside of their natural environment—in gardens, zoos, breeding programs, seed banks, or gene banks—has been widely advocated as an “insurance” against both climate change and other sources of biodiversity loss and impoverishment (Khoury et al., 2010). There are many examples of existing efforts of this type, some with global scope (e.g., Millennium Seed Bank, Svalbard Vault, Frozen Ark, Global Genome Initiative, and others; Lermen et al., 2009; Rawson et al., 2011). Knowledge of which genetic variants within a species have more potential for adaptation to climate change could help prioritize the material stored (Michalski et al., 2010).

Several issues remain largely unresolved (Li and Pritchard, 2009). The physiological, institutional, and economic sustainability of such efforts into the indefinite future is unclear. The fraction of the intraspecific variation that needs to be preserved for future viability and how much

genetic bias is introduced by collecting relatively small samples from restricted locations, and then later by the selection pressures inadvertently applied during *ex situ* maintenance are unknown. Despite some documented successes, it remains uncertain whether it is always possible to reintroduce species successfully into the wild after generations of *ex situ* conservation.

4.4.3. Consequences and Costs of Inaction and Benefits of Action

Failure to reduce the magnitude or rate of climate change will plausibly lead to changes (often decreases) in the value of ecosystem services provided, or incur costs in order to maintain or restore the services or adapt to their decline. There are several sources of such costs: administration and assessment, implementation, and opportunity costs, including financial cost. Owing to the number of assumptions made, knowledge gaps, and recognized uncertainties, such result should be employed with caution. A systematic review of costs related to ecosystems and climate change by Rodriguez-Labajos (2013) shows that the monetary and non-monetary costs are distributed across all ecosystem service categories. It also discusses the potential and limits of monetary cost calculations, and issues of timing, trade-offs, and the unequal distribution of costs.

A comprehensive monetary estimate of the effects of climate change on ecosystem service provision is not available. The Millennium Ecosystem Assessment (2005c,d,e) included climate change among the direct drivers of ecosystems change and devoted a chapter to the necessary responses. Building on results of the IPCC, the Millennium Ecosystem Assessment offered some estimated costs of action: complying with the Kyoto protocol for industrial countries would range between 0.2 and 2% of GDP; a modest stabilization target of 450 ppm CO₂ in the atmosphere over the 21st century would range from 0.02 to 0.1% of global-average GDP per year. TEEB (2009) underlined priorities in the ecosystem service-climate change coupling (reduction targets in relation to coral reefs, forest carbon markets and accounting, and ecosystem investment for mitigation), without going in depth into analysis of the cost types involved. The Cost of Policy Inaction (COPI) Project (ten Brink et al., 2008) estimated the monetary costs of not meeting the 2010 biodiversity goals. Their model incorporates climate change, among other pressures, through an impaired quality of land, in terms of species abundance in diverse land use categories. They conclude that the cumulative losses

Frequently Asked Questions

FAQ 4.7 | What are the economic costs of changes in ecosystems due to climate change?

Climate change will certainly alter the services provided by most ecosystems, and for high degrees of change, the overall impacts are most likely to be negative. In standard economics, the value of services provided by ecosystems are known as externalities, which are usually outside the market price system, difficult to evaluate, and often ignored.

A good example is the pollination of plants by bees and birds and other species, a service that may be negatively affected by climate change. Pollination is critical for the food supply as well as for overall environmental health. Its value has been estimated globally at US\$350 billion for the year 2010 (range of estimates of US\$200 to 500 billion).

of welfare due to land use changes, in terms of loss of ecosystem services, could reach an annual amount of EUR 14 trillion (based on 2007 values) in 2050, which may be equivalent to 7% of projected global GDP for that year. Eliasch (2008) estimates the damage costs to forests as reaching US\$1 trillion a year by 2100. The study used the probabilistic model employed by Stern (2006), which did not value effects on biodiversity or water-related ecosystem services.

The studies to date agree on the following points. First, climate change has already caused a reduction in ecosystem services that will become more severe as climate change continues. Second, ecosystem-based strategies to mitigate climate change are cost effective, although more difficult to implement (i.e., more costly) in intensively managed ecosystems such as farming lands. Third, accurately estimating the monetary costs of reduction in ecosystem services that are not marketed is difficult. The provision of monetized costs tends to sideline the non-monetized political, social, and environmental costs relevant for decision making. Finally, there is a large funding gap between the cost of actions necessary to protect ecosystem services against climate change and the actual resources available.

In addition to direct costs, further costs may result from trade-offs between services: for example, afforestation for climate mitigation and urban greening for climate adaptation may be costly in terms of water provision (Chisholm, 2010; Jenerette et al., 2011; Pataki et al., 2011). Traditional agriculture preserves soil carbon sinks, supports on-site biodiversity, and uses less fossil fuel than high-input agriculture (Martinez-Alier, 2011) but, due to the typically lower per hectare yields, may require a larger area to be dedicated to cropland. Leaving aside the contested (Searchinger et al., 2008; Plevin et al., 2010) effectiveness of biofuels as a mitigation strategy, there is evidence of their disruptive effect on food security, land tenure, labor rights, and biodiversity in several parts of the world (Obersteiner et al., 2010; Tirado et al., 2010).

4.4.4. Unintended Consequences of Adaptation and Mitigation

Actions taken within the terrestrial and freshwater system domain or in other sectors to mitigate or adapt to climate change can have unintended consequences. Some issues relevant to this section are also found in Section 14.7 and the Working Group III contribution to the AR5.

Several of the alternatives to fossil fuel require extensive use of the land surface and thus have a direct impact on terrestrial ecosystems and an indirect impact on inland water systems (Paterson et al., 2008; Turner et al., 2010). As an illustration, the RCP2.6 scenario involves both bioenergy and renewables as major components of the energy mix (Box 4-1; van Vuuren et al., 2011).

Policy shifts in developed countries favor the expansion of large-scale bioenergy production, which places new pressures on terrestrial and freshwater ecosystems (Searchinger et al., 2008; Lapola et al., 2010), either through direct use of land or water or indirectly by displacing food crops, which must then be grown elsewhere. Over the past decade there has been a global trend to reduced rates of forest loss; it is unclear if this will continue in the face of simultaneously rising food and biofuel

demand (Wise et al., 2009; Meyfroidt and Lambin, 2011). The EU Renewable Energy Sources Directive is estimated to have only a moderate influence on European forests provided that the price paid by the bioenergy producers remained below US\$50 to 60 per cubic meter of wood (Moiseyev et al., 2011). However, a doubled growth rate for bioenergy until 2030 would have major consequences for the global forest sector, including a reduction of forest stocks in Asia of 2 to 4% (Buongiorno et al. 2011). By 2100 in RCP2.6, bioenergy crops are projected to occupy approximately 4 million km², about 7% of global cultivated land projected at the time. Modification of the landscape and the fragmentation of habitats are major influences on extinction risks (Fischer and Lindenmayer, 2007), especially if native vegetation cover is reduced or degraded, human land use is intensive, and "natural" areas become disconnected. Hence, additional extensification of cultivated areas for energy crops may contribute to extinction risks. Some bioenergy crops may be invasive species (Raghu et al., 2006).

Abandoned former agricultural land could be used for biomass production (McAlpine et al., 2009). However, such habitats may be core elements in cultural landscapes of high conservation value, with European species-rich grasslands often developed from abandoned croplands (Hejman et al., 2013).

Damming of river systems for hydropower can cause fragmentation of the inland water habitat with implications for fish species, and monitoring studies indicate that flooding of ecosystems behind the dams can lead to declining populations, for example, of amphibians (Brandão and Araújo, 2007). Reservoirs can be a sink of CO₂ but also a source of biogenic CO₂ and CH₄; this issue is discussed in WG III AR5 Section 7.8.1.

Wind turbines can kill birds and bats (e.g., Barclay et al., 2007), and inappropriately sited wind farms can negatively impact on bird populations (Drewitt and Langston, 2006). Effects can be reduced by careful siting of turbines, for example by avoiding migration routes (Drewitt and Langston, 2006). Estimating mortality rates is complex and difficult (Smallwood, 2007) but techniques are being developed to inform siting decisions and impact assessments (Péron et al., 2013). Wind farms in Europe and the USA are estimated to cause between 0.3 and 0.4 wildlife fatalities per gigawatt-hour of electricity, compared to approximately 5.2 wildlife fatalities per gigawatt-hour for nuclear and fossil-fuel power stations (Sovacool, 2009; but see Willis, C.K.R. et al., 2010). One study found on-site bird populations to be generally affected more by windfarm construction than subsequent operation, with some populations recovering after construction (Pearce-Higgins et al., 2012).

Large-scale solar farms could impact local biodiversity if poorly sited, but the impact can be reduced with appropriate planning (Tsoutsos et al., 2005). Solar photovoltaic installations can decrease local surface albedo, giving a small positive radiative forcing. There are some plausible local circumstances in which this may be a consideration, but in general the climate effect is estimated to be 30 times smaller than the avoided radiative forcing arising from substituting fossil fuels with PV (Nemet, 2009).

Relocation or expansion of agricultural areas and settlements as climate change adaptation measures could pose risks of habitat fragmentation and loss similar to those discussed above in the context of mitigation

through bio-energy. Assisted migration (see Section 4.4.2.4) may directly conflict with other conservation priorities, for example by facilitating the introduction of invasive species (Maclachlan et al., 2007).

4.5. Emerging Issues and Key Uncertainties

Detecting the presence and location of thresholds in ecosystem response to climate change, specifically the type of thresholds characterized as tipping points, remains a major source of uncertainty with high potential consequences. In general (Field et al., 2007), negative feedbacks currently dominate the climate-ecosystem interaction. For most ecological processes, increasing magnitude of warming shifts the balance toward positive rather than negative feedbacks (Field et al., 2007). In several regions, such as the boreal ecosystems, positive feedbacks may become dominant, under moderate warming. For positive feedbacks to propagate into “runaway” processes leading to a new ecosystem state, the strength of the feedback has to exceed that of the initial perturbation. This has not as yet been demonstrated for any large-scale, plausible, and immanent ecological process, but the risk is non-negligible and the consequences if it did occur would be severe; thus further research is needed.

The issue of biophysical interactions between ecosystem state and the climate, over and above the effects mediated through GHGs, is emerging as significant in many areas. Such effects include those caused by changes in surface reflectivity (albedo) or the partitioning of energy between latent energy and sensible heat.

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

The consequences for species interactions of differing phenological or movement-based responses to climate change are insufficiently known and may make projections based on individual species models unreliable.

Studies of the combined effects of multiple simultaneous elements of global change, such as the effects of elevated CO₂ and rising tropospheric ozone on plant productivity—which have critical consequences for the future sink strength of the biosphere, as they are of similar magnitude but opposite sign—are needed as a supplement to the single-factor experiments. For example, uncertainty on the magnitude of CO₂ fertilization is key for forest responses to climate change, particularly in

tropical forests, woodlands, and savannas (Cox et al., 2013; Huntingford et al., 2013).

The effects of changes in the frequency or intensity of climate-related extreme events, such as floods, cyclones, heat waves, and exceptionally large fires on ecosystem change are probably equal to or greater than shifts in the mean values of climate variables. These effects are insufficiently studied and, in particular, are seldom adequately represented in ESMs.

Understanding of the rate of climate change that can be tracked or adapted to by organisms is as important as understanding the magnitude of change they can tolerate. Despite being explicitly required under Article 2 of the UNFCCC, rate studies are currently less developed and more uncertain than magnitude (equilibrium) studies. This includes evidence for the achievable migration rates of a range of species as well as the rate of micro-evolutionary change.

The capacity for, and limits to, ecological and evolutionary adaptive processes are known only in a few cases. The development and testing of human-assisted adaptation strategies for their cost-effectiveness in reducing risk are prerequisites for their widespread adoption.

The costs of the loss of biodiversity and ecosystem services as a result of climate change are known for only a few cases, or are associated with large uncertainties, as are the costs and benefits of assisting ecosystems and species to adapt to climate change.

References

- Aakala, T., T. Kuuluvainen, T. Wallenius, and H. Kauhanen, 2011: Tree mortality episodes in the intact *Picea abies*-dominated taiga in the Arkhangelsk region of northern European Russia. *Journal of Vegetation Science*, **22**(2), 322-333.
- Abatzoglou, J.T. and C.A. Kolden, 2011: Climate change in western US deserts: potential for increased wildfire and invasive annual grasses. *Rangeland Ecology & Management*, **64**(5), 471-478.
- Adamik, P. and M. Kral, 2008: Climate- and resource-driven long-term changes in dormice populations negatively affect hole-nesting songbirds. *Journal of Zoology*, **275**(3), 209-215.
- Adamik, P. and J. Pietruszkova, 2008: Advances in spring but variable autumnal trends in timing of inland wader migration. *Acta Ornithologica*, **43**(2), 119-128.
- Adams, H.D., C.H. Luce, D.D. Breshears, C.D. Allen, M. Weiler, V.C. Hale, A.M.S. Smith, and T.E. Huxman, 2012: Ecohydrological consequences of drought- and infestation-triggered tree die-off: insights and hypotheses. *Ecohydrology*, **5**(2), 145-159.
- Adrian, R., C.M. O'Reilly, H. Zagarese, S.B. Baines, D.O. Hessen, W. Keller, D.M. Livingstone, R. Sommaruga, D. Straile, E. Van Donk, G.A. Weyhenmeyer, and M. Winder, 2009: Lakes as sentinels of climate change. *Limnology and Oceanography*, **54**(6), 2283-2297.
- Ahl, D.E., S.T. Gower, S.N. Burrows, N.V. Shabanov, R.B. Myneni, and Y. Knyazikhin, 2006: Monitoring spring canopy phenology of a deciduous broadleaf forest using MODIS. *Remote Sensing of Environment*, **104**(1), 88-95.
- Ahola, M.P., T. Laaksonen, T. Eeva, and E. Lehikoinen, 2007: Climate change can alter competitive relationships between resident and migratory birds. *Journal of Animal Ecology*, **76**(6), 1045-1052.
- Aiello-Lammens, M.E., M.L. Chu-Agor, M. Convertino, R.A. Fischer, I. Linkov, and H.R. Akcakaya, 2011: The impact of sea-level rise on Snowy Plovers in Florida: integrating geomorphological, habitat, and metapopulation models. *Global Change Biology*, **17**(12), 3644-3654.
- Ainsworth, E.A., C.R. Yendrek, S. Sitoh, W.J. Collins, and L.D. Emberson, 2012: The effects of tropospheric ozone on net primary productivity and implications for climate change. *Annual Review of Plant Biology*, **63**(1), 637-661.

- Aitken, S.N., S. Yeaman, J.A. Holliday, T.L. Wang, and S. Curtis-McLane, 2008: Adaptation, migration or extirpation: climate change outcomes for tree populations. *Evolutionary Applications*, **1**(1), 95-111.
- Alahuhta, J., J. Heino, and M. Luoto, 2011: Climate change and the future distributions of aquatic macrophytes across boreal catchments. *Journal of Biogeography*, **38**(2), 383-393.
- Albert, K.R., J. Kongstad, I.K. Schmidt, H. Ro-Poulsen, T.N. Mikkelsen, A. Michelsen, L. van der Linden, and C. Beier, 2012: Temperate heath plant response to dry conditions depends on growth strategy and less on physiology. *Acta Oecologica-International Journal of Ecology*, **45**, 79-87.
- Albert, K.R., H. Ro-Poulsen, T.N. Mikkelsen, A. Michelsen, L. Van der Linden, and C. Beier, 2011: Effects of elevated CO₂, warming and drought episodes on plant carbon uptake in a temperate heath ecosystem are controlled by soil water status. *Plant Cell and Environment*, **34**(7), 1207-1222.
- Aldous, A., J. Fitzsimons, B. Richter, and L. Bach, 2011: Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. *Marine and Freshwater Research*, **62**(3), 223-231.
- Alencar, A., D.C. Nepstad, and M.d.C. Vera Diaz, 2006: Forest understory fire in the Brazilian Amazon in ENSO and non-ENSO years: area burned and committed carbon emissions. *Earth Interactions*, **10**, 6, 1-17, doi:10.1175/EI150.1.
- Alencar, A., G.P. Asner, D. Knapp, and D. Zarin, 2011: Temporal variability of forest fires in eastern Amazonia. *Ecological Applications*, **21**(7), 2397-2412.
- Alexander, H.D., M.C. Mack, S. Goetz, M. Loranty, P.S.A. Beck, K. Earl, S. Zimov, S. Davydov, and C.C. Thompson, 2012: Carbon accumulation patterns during post-fire succession in cajander larch (*Larix cajanderi*) forests of Siberia. *Ecosystems*, **15**, 1065-1082.
- Ali, A.A., O. Blarquez, M.P. Girardin, C. Hely, F. Tinquaut, A. El Guellab, V. Valsecchi, A. Terrier, L. Bremond, A. Genries, S. Gauthier, and Y. Bergeron, 2012: Control of the multimillennial wildfire size in boreal North America by spring climatic conditions. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(51), 20966-20970.
- Alkama, R., M. Gageyama, and G. Ramstein, 2012: A sensitivity study to global desertification in cold and warm climates: results from the IPSL OAGCM model. *Climate Dynamics*, **38**(7-8), 1629-1647.
- Alkemade, R., M. van Oorschot, L. Miles, C. Nellemann, M. Bakkenes, and B. ten Brink, 2009: GLOBIO3: a framework to investigate options for reducing global terrestrial biodiversity loss. *Ecosystems*, **12**(3), 374-390.
- Allan, J.D., 2004: Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology Evolution and Systematics*, **35**, 257-284.
- Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears, E.H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J.H. Lim, G. Allard, S.W. Running, A. Semerci, and N. Cobb, 2010: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, **259**(4), 660-684.
- Allen, J.R.M., T. Hickler, J.S. Singarayer, M.T. Sykes, P.J. Valdes, and B. Huntley, 2010: Last glacial vegetation of northern Eurasia. *Quaternary Science Reviews*, **29**(19-20), 2604-2618.
- Alley, R.B., J. Marotzke, W.D. Nordhaus, J.T. Overpeck, D.M. Peteet, R.A. Pielke, R.T. Pierrehumbert, P.B. Rhines, T.F. Stocker, L.D. Talley, and J.M. Wallace, 2003: Abrupt climate change. *Science*, **299**(5615), 2005-2010.
- Anchukaitis, K.J. and M.N. Evans, 2010: Tropical cloud forest climate variability and the demise of the Monteverde golden toad. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(11), 5036-5040.
- Anderegg, W.R.L., L.D.L. Anderegg, C. Sherman, and D.S. Karp, 2012: Effects of widespread drought-induced aspen mortality on understory plants. *Conservation Biology*, **26**(6), 1082-1090.
- Anderegg, W.R.L., J.M. Kane, and L.D.L. Anderegg, 2013a: Consequences of widespread tree mortality triggered by drought and temperature stress. *Nature Climate Change*, **3**(1), 30-36.
- Anderegg, W.R.L., L. Plavcová, L.D.L. Anderegg, U.G. Hacke, J.A. Berry, and C.B. Field, 2013b: Drought's legacy: multiyear hydraulic deterioration underlies widespread aspen forest die-off and portends increased future risk. *Global Change Biology*, **19**(4), 1188-1196.
- Anderson, J.T., A.M. Panetta, and T. Mitchell-Olds, 2012a: Evolutionary and ecological responses to anthropogenic climate change. *Plant Physiology*, **160**(4), 1728-1740.
- Anderson, J.T., D.W. Inouye, A.M. McKinney, R.I. Colautti, and T. Mitchell-Olds, 2012b: Phenotypic plasticity and adaptive evolution contribute to advancing flowering phenology in response to climate change. *Proceedings of the Royal Society B*, **279**(1743), 3843-3852.
- Anderson, R.G., J.G. Canadell, J.T. Randerson, R.B. Jackson, B.A. Hungate, D.D. Baldocchi, G.A. Ban-Weiss, G.B. Bonan, K. Caldeira, L. Cao, N.S. Diffenbaugh, K.R. Gurney, L.M. Kueppers, B.E. Law, S. Luysaert, and T.L. O'Halloran, 2011: Biophysical considerations in forestry for climate protection. *Frontiers in Ecology and the Environment*, **9**(3), 174-182.
- Andreae, M.O., D. Rosenfeld, P. Artaxo, A.A. Costa, G.P. Frank, K.M. Longo, and M.A.F. Silva-Dias, 2004: Smoking rain clouds over the Amazon. *Science*, **303**, 1337-1342.
- Andreu-Hayles, L., O. Planells, E. Gutiérrez, E. Muntan, G. Helle, K.J. Anchukaitis, and G.H. Schleser, 2011: Long tree-ring chronologies reveal 20th century increases in water-use efficiency but no enhancement of tree growth at five Iberian pine forests. *Global Change Biology*, **17**(6), 2095-2112.
- Angassa, A. and G. Oba, 2008: Effects of management and time on mechanisms of bush encroachment in southern Ethiopia. *African Journal of Ecology*, **46**(2), 186-196.
- Angeler, D.G. and W. Goedkoop, 2010: Biological responses to liming in boreal lakes: an assessment using plankton, macroinvertebrate and fish communities. *Journal of Applied Ecology*, **47**(2), 478-486.
- Angert, A.L., L.G. Crozier, L.J. Rissler, S.E. Gilman, J.J. Tewksbury, and A.J. Chunco, 2011: Do species' traits predict recent shifts at expanding range edges? *Ecology Letters*, **14**(7), 677-689.
- Angetter, L.S., S. Lotter, and D. Rodder, 2011: Climate niche shift in invasive species: the case of the brown anole. *Biological Journal of the Linnean Society*, **104**(4), 943-954.
- Anyamba, A. and C.J. Tucker, 2005: Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981-2003. *Journal of Arid Environments*, **63**(3), 596-614.
- Aragão, L., Y. Malhi, N. Barbier, A. Lima, Y. Shimabukuro, L. Anderson, and S. Saatchi, 2008: Interactions between rainfall, deforestation and fires during recent years in the Brazilian Amazonia. *Philosophical Transactions of the Royal Society B*, **363**(1498), 1779-1785.
- Araujo, M.B. and A.T. Peterson, 2012: Uses and misuses of bioclimatic envelope modeling. *Ecology*, **93**(7), 1527-1539.
- Araujo, M.B., D. Alagador, M. Cabeza, D. Noguez-Bravo, and W. Thuiller, 2011: Climate change threatens European conservation areas. *Ecology Letters*, **14**(5), 484-492.
- Archibald, S., D.P. Roy, B.W. van Wilgen, and R.J. Scholes, 2009: What limits fire? An examination of drivers of burnt area in southern Africa. *Global Change Biology*, **15**(3), 613-630.
- Arenas, M., N. Ray, M. Currat, and L. Excoffier, 2012: Consequences of range contractions and range shifts on molecular diversity. *Molecular Biology and Evolution*, **29**(1), 207-218.
- Arisemendi, I., S.L. Johnson, J.B. Dunham, R. Haggerty, and D. Hockman-Wert, 2012: The paradox of cooling streams in a warming world: Regional climate trends do not parallel variable local trends in stream temperature in the Pacific continental United States. *Geophysical Research Letters*, **39**, L10401, doi:10.1029/2012GL051448.
- Armenteras-Pascual, D., J. Retana-Alumbreros, R. Molowny-Horas, R.M. Roman-Cuesta, F. Gonzalez-Alonso, and M. Morales-Rivas, 2011: Characterising fire spatial pattern interactions with climate and vegetation in Colombia. *Agricultural and Forest Meteorology*, **151**(3), 279-289.
- Arnell, A., S.P. Harrison, S. Zaehle, K. Tsigaridis, S. Menon, P.J. Bartlein, J. Feichter, A. Korhola, M. Kulmala, D. O'Donnell, G. Schurgers, S. Sorvari, and T. Vesala, 2010: Terrestrial biogeochemical feedbacks in the climate system. *Nature Geoscience*, **3**(8), 525-532.
- Arora, V.K. and A. Montenegro, 2011: Small temperature benefits provided by realistic afforestation efforts. *Nature Geoscience*, **4**(8), 514-518.
- Arthington, A.H., S.E. Bunn, N.L. Poff, and R.J. Naiman, 2006: The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications*, **16**(4), 1311-1318.
- Arthington, A.H., R.J. Naiman, M.E. McClain, and C. Nilsson, 2010: Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. *Freshwater Biology*, **55**(1), 1-16.
- Ask, J., J. Karlsson, L. Persson, P. Ask, P. Bystrom, and M. Jansson, 2009: Terrestrial organic matter and light penetration: Effects on bacterial and primary production in lakes. *Limnology and Oceanography*, **54**(6), 2034-2040.
- Aubin, I., C.M. Garbe, S. Colombo, C.R. Drever, D.W. McKinney, C. Messier, J. Pedlar, M.A. Saner, L. Venier, A.M. Wellstead, R. Winder, E. Witten, and C. Ste-Marie, 2011: Why we disagree about assisted migration: ethical implications of a key

- debate regarding the future of Canada's forests. *Forestry Chronicle*, **87(6)**, 755-765.
- Aufdenkampe, A.K., E. Mayorga, P.A. Raymond, J.M. Melack, S.C. Doney, S.R. Alin, R.E. Aalto, and K. Yoo**, 2011: Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Frontiers in Ecology and the Environment*, **9(1)**, 53-60.
- Axford, Y., J.P. Briner, C.A. Cooke, D.R. Francis, N. Michelutti, G.H. Miller, J.P. Smol, E.K. Thomas, C.R. Wilson, and A.P. Wolfe**, 2009: Recent changes in a remote Arctic lake are unique within the past 200,000 years. *Proceedings of the National Academy of Sciences of the United States of America*, **106(44)**, 18443-18446.
- Baccini, A., S.J. Goetz, W.S. Walker, N.T. Laporte, M. Sun, D. Sulla-Menasha, J. Hackler, P.S.A. Beck, R. Dubayah, M.A. Fiedl, S. Samanta, and R.A. Houghton**, 2012: Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change*, **2(3)**, 182-185.
- Bai, Z.G., D.L. Dent, L. Olsson, and M.E. Schaepman**, 2008: Proxy global assessment of land degradation. *Soil Use and Management*, **24(3)**, 223-234.
- Bala, G., K. Caldeira, M. Wickett, T.J. Phillips, D.B. Lobell, C. Delire, and A. Mirin**, 2007: Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences of the United States of America*, **104(16)**, 6550-6555.
- Balch, J.K., D.C. Nepstad, P.M. Brando, L.M. Curran, O. Portela, O. de Carvalho, and P. Lefebvre**, 2008: Negative fire feedback in a transitional forest of southeastern Amazonia. *Global Change Biology*, **14(10)**, 2276-2287.
- Balian, E.V., H. Segers, C. Leveque, and K. Martens**, 2008: The freshwater animal diversity assessment: an overview of the results. *Hydrobiologia*, **595(1)**, 627-637.
- Balint, M., S. Domisch, C.H.M. Engelhardt, P. Haase, S. Lehrian, J. Sauer, K. Theissinger, S.U. Pauls, and C. Nowak**, 2011: Cryptic biodiversity loss linked to global climate change. *Nature Climate Change*, **1(6)**, 313-318.
- Ball, J.T., I.E. Woodrow, and J.A. Berry**, 1987: A model predicting stomatal conductance and its to the control of photosynthesis under different environmental conditions. In: *Progress in Photosynthesis Research: Proceedings of the Vllth International Congress on Photosynthesis, Providence, Rhode Island, USA, August 10-15, Vol. 2* [Biggins, I. (ed.)]. Martinus Nijhoff Publishers, Leiden, Netherlands, pp. 221-224.
- Barber, V.A., G.P. Juday, and B.P. Finney**, 2000: Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature*, **405(6787)**, 668-673.
- Barbet-Massin, M., W. Thuiller, and F. Jiguet**, 2012: The fate of European breeding birds under climate, land-use and dispersal scenarios. *Global Change Biology*, **18(3)**, 881-890.
- Barbosa, I.C.R., I.H. Koehler, K. Auerswald, P. Lups, and S. Hans**, 2010: Last-century changes of alpine grassland water-use efficiency: a reconstruction through carbon isotope analysis of a time-series of Capra ibex horns. *Global Change Biology*, **16(4)**, 1171-1180.
- Barbraud, C. and H. Weimerskirch**, 2006: Antarctic birds breed later in response to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **103(16)**, 6248-6251.
- Barbraud, C., M. Gavrilov, Y. Mizin, and H. Weimerskirch**, 2011: Comparison of emperor penguin declines between Pointe Geologie and Haswell Island over the past 50 years. *Antarctic Science*, **23(5)**, 461-468.
- Barclay, R.M.R., E.F. Baerwald, and J.C. Gruver**, 2007: Variation in bat and bird fatalities at wind energy facilities: assessing the effects of rotor size and tower height. *Canadian Journal of Zoology / Revue Canadienne De Zoologie*, **85(3)**, 381-387.
- Barlow, J. and C.A. Peres**, 2008: Fire-mediated dieback and compositional cascade in an Amazonian forest. *Philosophical Transactions of the Royal Society B*, **363(1498)**, 1787-1794.
- Barnosky, A.D., N. Matzke, S. Tomiya, G.O.U. Wogan, B. Swartz, T.B. Quental, C. Marshall, J.L. McGuire, E.L. Lindsey, K.C. Maguire, B. Mersey, and E.A. Ferrer**, 2011: Has the Earth's sixth mass extinction already arrived? *Nature*, **471(7336)**, 51-57.
- Barnosky, A.D., E.A. Hadly, J. Bascompte, E.L. Berlow, J.H. Brown, M. Fortelius, W.M. Getz, J. Harte, A. Hastings, P.A. Marquet, N.D. Martinez, A. Mooers, P. Roopnarine, G. Vermeij, J.W. Williams, R. Gillespie, J. Kitzes, C. Marshall, N. Matzke, D.P. Mindell, E. Revilla, and A.B. Smith**, 2012: Approaching a state shift in Earth's biosphere. *Nature*, **486(7401)**, 52-58.
- Bartholow, J.M.**, 2005: Recent water temperature trends in the lower Klamath River, California. *North American Journal of Fisheries Management*, **25(1)**, 152-162.
- Bartomeus, I., J.S. Ascher, D. Wagner, B.N. Danforth, S. Colla, S. Kornbluth, and R. Winfree**, 2011: Climate-associated phenological advances in bee pollinators and bee-pollinated plants. *Proceedings of the National Academy of Sciences of the United States of America*, **108(51)**, 20645-20649.
- Bateman, B.L., J. VanDerWal, S.E. Williams, and C.N. Johnson**, 2012: Biotic interactions influence the projected distribution of a specialist mammal under climate change. *Diversity and Distributions*, **18(9)**, 861-872.
- Bateman, B.L., H.T. Murphy, A.E. Reside, K. Mokany, and J. VanDerWal**, 2013: Appropriateness of full-, partial- and no-dispersal scenarios in climate change impact modelling. *Diversity and Distributions*, **19(10)**, 1224-1234.
- Bathiany, S., M. Claussen, V. Brovkin, T. Raddatz, and V. Gayler**, 2010: Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI earth system model. *Biogeosciences*, **7(5)**, 1383-1399.
- Battarbee, R.W., M. Kernan, and N. Rose**, 2009: Threatened and stressed mountain lakes of Europe: assessment and progress. *Aquatic Ecosystem Health & Management*, **12(2)**, 118-128.
- Beale, C.M. and J.J. Lennon**, 2012: Incorporating uncertainty in predictive species distribution modelling. *Philosophical Transactions of the Royal Society B*, **367(1586)**, 247-258.
- Beaumont, L.J., A. Pitman, S. Perkins, N.E. Zimmermann, N.G. Yoccoz, and W. Thuiller**, 2011: Impacts of climate change on the world's most exceptional ecoregions. *Proceedings of the National Academy of Sciences of the United States of America*, **108(6)**, 2306-2311.
- Beck, H.E., T.R. McVicar, A.I.L. van Dijk, J. Schellenkens, R.A.M. de Jeu, and L.A. Bruijnzeel**, 2011: Global evaluation of four AVHRR-NDVI data sets: intercomparison and assessment against Landsat imagery. *Remote Sensing of Environment*, **115(10)**, 2547-2563.
- Beck, P.S.A. and S.J. Goetz**, 2011: Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: ecological variability and regional differences. *Environmental Research Letters*, **6(4)**, 045501, doi:10.1088/1748-9326/6/4/045501.
- Beck, P.S.A., G.P. Juday, A. Claire, W. Steve, S. Emily, H. Patricia, D.H. James, and S.J. Goetz**, 2011: Changes in forest productivity across Alaska are captured in satellite and tree ring records. *Ecology Letters*, **14(4)**, 373-379.
- Beerling, D.J. and C.P. Osborne**, 2006: The origin of the savanna biome. *Global Change Biology*, **12(11)**, 2023-2031.
- Beier, C., I.K. Schmidt, and H.L. Kristensen**, 2004: Effects of climate and ecosystem disturbances on biogeochemical cycling in a semi-natural terrestrial ecosystem. *Water, Air and Soil Pollution: Focus*, **4**, 191-206.
- Beier, C., B.A. Emmett, J. Penuelas, I.K. Schmidt, A. Tietema, M. Estiarte, P. Gundersen, L. Llorens, T. Riis-Nielsen, A. Sowerby, and A. Gorissen**, 2008: Carbon and nitrogen cycles in European ecosystems respond differently to global warming. *Science of the Total Environment*, **407(1)**, 692-697.
- Beilman, D.W., G.M. MacDonald, L.C. Smith, and P.J. Reimer**, 2009: Carbon accumulation in peatlands of West Siberia over the last 2000 years. *Global Biogeochemical Cycles*, **23(1)**, GB1012, doi:10.1029/2007GB003112.
- Bell, G.**, 2013: Evolutionary rescue and the limits of adaptation. *Philosophical Transactions of the Royal Society B*, **368(1610)**, 20120080, doi:10.1098/rstb.2012.0080.
- Bell, G. and A. Gonzalez**, 2009: Evolutionary rescue can prevent extinction following environmental change. *Ecology Letters*, **12(9)**, 942-948.
- Bellard, C., C. Bertelsmeier, P. Leadley, W. Thuiller, and F. Courchamp**, 2012: Impacts of climate change on the future of biodiversity. *Ecology Letters*, **15(4)**, 365-377.
- Bellard, C., W. Thuiller, B. Leroy, P. Genovesi, M. Bakkenes, and F. Courchamp**, 2013: Will climate change promote future invasions? *Global Change Biology*, **19(12)**, 3740-3748.
- Bellassen, V., N. Viovy, S. Luyssaert, G. Le Maire, M.J. Schelhaas, and P. Ciais**, 2011: Reconstruction and attribution of the carbon sink of European forests between 1950 and 2000. *Global Change Biology*, **17(11)**, 3274-3292.
- Belyazid, S., D. Kurz, S. Braun, H. Sverdrup, B. Rihm, and J.P. Hettelingh**, 2011: A dynamic modelling approach for estimating critical loads of nitrogen based on plant community changes under a changing climate. *Environmental Pollution*, **159(3)**, 789-801.
- Bentz, B.J., J. Régnière, C.J. Fettig, E.M. Hansen, J.L. Hayes, J.A. Hicke, R.G. Kelsey, J.F. Negrón, and S.J. Seybold**, 2010: Climate change and bark beetles of the Western United States and Canada: direct and indirect effects. *Bioscience*, **60(8)**, 602-613.
- Berg, M.P., E.T. Kiers, G. Driessen, M. Van Der Heijden, B.W. Kooi, F. Kuenen, M. Liefting, H.A. Verhoef, and J. Eilers**, 2010: Adapt or disperse: understanding species persistence in a changing world. *Global Change Biology*, **16(2)**, 587-598.

- Bergeron, Y., D. Cyr, M.P. Girardin, and C. Carcaillet, 2010: Will climate change drive 21st century burn rates in Canadian boreal forest outside of its natural variability: collating global climate model experiments with sedimentary charcoal data. *International Journal of Wildland Fire*, **19**(8), 1127-1139.
- Bergström, A.K. and M. Jansson, 2006: Atmospheric nitrogen deposition has caused nitrogen enrichment and eutrophication of lakes in the northern hemisphere. *Global Change Biology*, **12**, 635-643.
- Berkes, F., J. Colding, and C. Folke (eds.), 2003: *Navigating Social-Ecological Systems. Building Resilience for Complexity and Change*. Cambridge University Press, Cambridge, UK, 393 pp.
- Bernacchi, C.J., A.D.B. Leakey, L.E. Heady, P.B. Morgan, F.G. Dohleman, J.M. McGrath, K.M. Gillespie, V.E. Wittig, A. Rogers, S.P. Long, and D.R. Ort, 2006: Hourly and seasonal variation in photosynthesis and stomatal conductance of soybean grown at future CO₂ and ozone concentrations for 3 years under fully open-air field conditions. *Plant Cell and Environment*, **29**(11), 2077-2090.
- Bernhardt, E.L., T.N. Hollingsworth, and F.S. Chapin III, 2011: Fire severity mediates climate-driven shifts in understory community composition of black spruce stands of interior Alaska. *Journal of Vegetation Science*, **22**(1), 32-44.
- Bertaux, D., D. Reale, A.G. McAdam, and S. Boutin, 2004: Keeping pace with fast climate change: can Arctic life count on evolution? *Integrative and Comparative Biology*, **44**(2), 140-151.
- Bertelsmeier, C., G. Luque, and F. Courchamp, 2012: Global warming may freeze the invasion of big-headed ants. *Biological Invasions*, **15**(7), 1561-1572.
- Bertrand, R., J. Lenoir, C. Piedallu, G. Riofrio-Dillon, P. de Ruffray, C. Vidal, J.C. Pierrat, and J.C. Gegout, 2011: Changes in plant community composition lag behind climate warming in lowland forests. *Nature*, **479**(7374), 517-520.
- Bertzky, M., B. Dickson, R. Galt, E. Glen, M. Harley, N. Hodgson, G. Keder, I. Lyenko, M. Pooley, C. Ravilious, T. Sajwaj, R. Schiopu, Y. de Soye, and G. Tucker, 2010: *Impacts of Climate Change and Selected Renewable Energy Infrastructures on EU Biodiversity and the Natura 2000 Network. Summary Report*. European Commission and International Union for Conservation of Nature, Brussels. <http://ec.europa.eu/environment/nature/climatechange/pdf/study.pdf>.
- Betts, R.A., N.W. Arnell, P. Boorman, S.E. Cornell, J.I. House, N.R. Kaye, M.P. McCarthy, D. McNeill, M.G. Sanderson, and A.J. Wiltshire, 2012: Climate change impacts and adaptation: an earth system view. In: *Understanding the Earth System: Global Change Science for Application* [Cornell, S., C. Prentice, J. House, and C. Downy (eds.)]. Cambridge University Press, Cambridge, UK, pp. 160-201.
- Betts, R.A., N. Golding, P. Gonzalez, J. Gornall, R. Kahana, G. Kay, L. Mitchell, and A. Wiltshire, 2013: Climate and land use change impacts on global terrestrial ecosystems, fire, and river flows in the HadGEM2-ES Earth System Model using the Representative Concentration Pathways. *Biogeosciences Discussions*, **10**, 6171-6223. doi:10.5194/bgd-10-6171-2013.
- Bhatt, U.S., D.A. Walker, M.K. Reynolds, J.C. Comiso, H.E. Epstein, G.S. Jia, R. Gens, J.E. Pinzon, C.J. Tucker, C.E. Tweedie, and P.J. Webber, 2010: Circumpolar Arctic tundra vegetation change is linked to sea ice decline. *Earth Interactions*, **14**, 8, doi:10.1175/2010EI315.1.
- Biesmeijer, J.C., S.P.M. Roberts, M. Reemer, R. Ohlemuller, M. Edwards, T. Peeters, A.P. Schaffers, S.G. Potts, R. Kleukers, C.D. Thomas, J. Settele, and W.E. Kunin, 2006: Parallel declines in pollinators and insect-pollinated plants in Britain and The Netherlands. *Science*, **313**(5785), 351-354.
- Biggs, D., R. Biggs, V. Dakos, R.J. Scholes, and M. Schoon, 2011: Are we entering an era of concatenated global crises? *Ecology and Society*, **16**(2), 27, www.ecologyandsociety.org/vol16/iss2/art27.
- Biggs, R., S.R. Carpenter, and W.A. Brock, 2009: Turning back from the brink: detecting an impending regime shift in time to avert it. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(3), 826-831.
- Birdsey, R.A., K.S. Pregitzer, and A. Lucier, 2006: Forest carbon management in the United States: 1600-2100. *Journal of Environmental Quality*, **35**(4), 1461-1469.
- Bleeker, A., W.K. Hicks, E. Dentener, J. Galloway, and J.W. Erisman, 2011: N deposition as a threat to the World's protected areas under the Convention on Biological Diversity. *Environmental Pollution*, **159**(10), 2280-2288.
- Blok, D., M.M.P.D. Heijmans, G. Schaepman-Strub, A.V. Kononov, T.C. Maximov, and F. Berendse, 2010: Shrub expansion may reduce summer permafrost thaw in Siberian tundra. *Global Change Biology*, **16**(4), 1296-1305.
- Bloor, J., P. Pichon, R. Falcimagne, P. Leadley, and J.-F. Soussana, 2010: Effects of warming, summer drought, and CO₂ enrichment on aboveground biomass production, flowering phenology, and community structure in an upland grassland ecosystem. *Ecosystems*, **13**(6), 888-900.
- BMT WBM, 2010: *Kakadu – Vulnerability to Climate Change Impacts*. A report to the Australian Government Department of Climate Change and Energy Efficiency. Australian Government, Department of Climate Change and Energy Efficiency, Canberra, ACT, Australia, 226 pp.
- Bobbink, R., K. Hicks, J. Galloway, T. Spranger, R. Alkemade, M. Ashmore, M. Bustamante, S. Cinderby, E. Davidson, F. Dentener, B. Emmett, J.W. Erisman, M. Fenn, F. Gilliam, A. Nordin, L. Pardo, and W. De Vries, 2010: Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. *Ecological Applications*, **20**(1), 30-59.
- Bockheim, J., G. Vieira, M. Ramos, J. Lopez-Martinez, E. Serrano, M. Guglielmin, K. Wilhelm, and A. Nieuwendam, 2013: Climate warming and permafrost dynamics in the Antarctic Peninsula region. *Global and Planetary Change*, **100**, 215-223.
- Boggs, C.L. and D.W. Inouye, 2012: A single climate driver has direct and indirect effects on insect population dynamics. *Ecology Letters*, **15**(5), 502-508.
- Boisvenue, C. and S.W. Running, 2006: Impacts of climate change on natural forest productivity - evidence since the middle of the 20th century. *Global Change Biology*, **12**(5), 862-882.
- Bolte, A. and B. Degen, 2010: Forest adaptation to climate change – options and limitations. *Landbauforschung*, **60**(3), 111-117.
- Bolte, A., C. Ammer, M. Lof, P. Madsen, G.J. Nabuurs, P. Schall, P. Späthelf, and J. Rock, 2009: Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. *Scandinavian Journal of Forest Research*, **24**(6), 473-482.
- Bolte, A., L. Hilbrig, B. Grundmann, F. Kampf, J. Brunet, and A. Roloff, 2010: Climate change impacts on stand structure and competitive interactions in a southern Swedish spruce-beech forest. *European Journal of Forest Research*, **129**(3), 261-276.
- Bomhard, B., D.M. Richardson, J.S. Donaldson, G.O. Hughes, G.F. Midgley, D.C. Raimondo, A.G. Rebelo, M. Rouget, and W. Thuiller, 2005: Potential impacts of future land use and climate change on the Red List status of the Proteaceae in the Cape Floristic Region, South Africa. *Global Change Biology*, **11**(9), 1452-1468.
- Bonan, G.B., 2008: Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science*, **320**(5882), 1444-1449.
- Bond, N.R., P.S. Lake, and A.H. Arthington, 2008: The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia*, **600**(1), 3-16.
- Bond, W.J. and J.J. Midgley, 2001: Ecology of sprouting in woody plants: the persistence niche. *Trends in Ecology & Evolution*, **16**(1), 45-51.
- Bond, W.J. and G.F. Midgley, 2012: Carbon dioxide and the uneasy interactions of trees and savannah grasses. *Philosophical Transactions of the Royal Society B*, **367**(1588), 601-612.
- Bond-Lamberty, B. and A. Thomson, 2010: Temperature-associated increases in the global soil respiration record. *Nature*, **464**(7288), 579-582.
- Bond-Lamberty, B., S.D. Peckham, D.E. Ahl, and S.T. Gower, 2007: Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature*, **450**(7166), 89-92.
- Bonfils, C.J.W., T.J. Phillips, D.M. Lawrence, P. Cameron-Smith, W.J. Riley, and Z.M. Subin, 2012: On the influence of shrub height and expansion on northern high latitude climate. *Environmental Research Letters*, **7**(1), 015503, doi:10.1088/1748-9326/7/1/015503.
- Bontemps, J.D., J.C. Herve, J.M. Leban, and J.F. Dhote, 2011: Nitrogen footprint in a long-term observation of forest growth over the twentieth century. *Trees – Structure and Function*, **25**(2), 237-251.
- Booker, K., L. Huntsinger, J.W. Bartolome, N.F. Sayre, and W. Stewart, 2013: What can ecological science tell us about opportunities for carbon sequestration on arid rangelands in the United States? *Global Environmental Change: Human and Policy Dimensions*, **23**(1), 240-251.
- Booth, R.K., S.T. Jackson, S.L. Forman, J.E. Kutzbach, E.A. Bettis, J. Kreig, and D.K. Wright, 2005: A severe centennial-scale drought in mid-continental North America 4200 years ago and apparent global linkages. *Holocene*, **15**(3), 321-328.
- Bosio, J., M. Johansson, T.V. Callaghan, B. Johansen, and T.R. Christensen, 2012: Future vegetation changes in thawing subarctic mires and implications for greenhouse gas exchange – a regional assessment. *Climatic Change*, **115**(2), 379-398.
- Both, C., S. Bouwhuis, C.M. Lessels, and M.E. Visser, 2006: Climate change and population declines in a long-distance migratory bird. *Nature*, **441**(7089), 81-83.
- Both, C., C.A.M. Van Turnhout, R.G. Bijlsma, H. Siepel, A.J. Van Strien, and R.P.B. Foppen, 2010: Avian population consequences of climate change are most severe for long-distance migrants in seasonal habitats. *Proceedings of the Royal Society B*, **277**(1685), 1259-1266.

- Botkin, D.B., H. Saxe, M.B. Araujo, R. Betts, R.H.W. Bradshaw, T. Cedhagen, P. Chesson, T.P. Dawson, J.R. Etterson, D.P. Faith, S. Ferrier, A. Guisan, A.S. Hansen, D.W. Hilbert, C. Loehle, C. Margules, M. New, M.J. Sobel, and D.R.B. Stockwell, 2007:** Forecasting the effects of global warming on biodiversity. *BioScience*, **57(3)**, 227-236.
- Boutton, T.W., J.D. Liao, T.R. Filley, and S.R. Archer, 2009:** Belowground carbon storage and dynamics accompanying woody plant encroachment in a subtropical savanna. *Soil Carbon Sequestration and the Greenhouse Effect* [Lal, R. and R. Follett (eds.)]. 2nd edn., Soil Science Society of America, Inc., Madison, WI, USA, pp. 181-205.
- Bowman, D., J.K. Balch, P. Artaxo, W.J. Bond, J.M. Carlson, M.A. Cochrane, C.M. D'Antonio, R.S. DeFries, J.C. Doyle, S.P. Harrison, F.H. Johnston, J.E. Keeley, M.A. Krawchuk, C.A. Kull, J.B. Marston, M.A. Moritz, I.C. Prentice, C.I. Roos, A.C. Scott, T.W. Swetnam, G.R. van der Werf, and S.J. Pyne, 2009:** Fire in the Earth system. *Science*, **324(5926)**, 481-484.
- Bowman, D.M.J.S., B.P. Murphy, and D.S. Banfai, 2011:** Has global environmental change caused monsoon rainforests to expand in the Australian monsoon tropics? *Landscape Ecology*, **25(8)**, 1247-1260.
- Bradley, B.A., M. Oppenheimer, and D.S. Wilcove, 2009:** Climate change and plant invasions: restoration opportunities ahead? *Global Change Biology*, **15(6)**, 1511-1521.
- Bradley, B.A., D.M. Blumenthal, D.S. Wilcove, and L.H. Ziska, 2010:** Predicting plant invasions in an era of global change. *Trends in Ecology & Evolution*, **25(5)**, 310-318.
- Brandão, R.A. and A.F.B. Araújo, 2007:** Changes in anuran species richness and abundance resulting from hydroelectric dam flooding in central Brazil. *Biotropica*, **40(2)**, 263-266.
- Brando, P.M., S.J. Goetz, A. Baccini, D.C. Nepstad, P.S.A. Beck, and M.C. Christman, 2010:** Seasonal and interannual variability of climate and vegetation indices across the Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, **107(33)**, 14685-14690.
- Brando, P.M., D.C. Nepstad, J.K. Balch, B. Bolker, M.C. Christman, M.T. Coe, and F.E. Putz, 2012:** Fire-induced tree mortality in a neotropical forest: the roles of bark traits, tree size, wood density and fire behavior. *Global Change Biology*, **18(2)**, 630-641.
- Brasier, C. and J. Webber, 2010:** Plant pathology: Sudden larch death. *Nature*, **466(7308)**, 824-825.
- Breshears, D.D., 2006:** The grassland-forest continuum: trends in ecosystem properties for woody plant mosaics? *Frontiers in Ecology and the Environment*, **4(2)**, 96-104.
- Breshears, D.D., N.S. Cobb, P.M. Rich, K.P. Price, C.D. Allen, R.G. Balice, W.H. Romme, J.H. Kastens, M.L. Floyd, J. Belnap, J.J. Anderson, O.B. Myers, and C.W. Meyer, 2005:** Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences of the United States of America*, **102(42)**, 15144-15148.
- Bridle, J.R., J. Polechova, M. Kawata, and R.K. Butlin, 2010:** Why is adaptation prevented at ecological margins? New insights from individual-based simulations. *Ecology Letters*, **13(4)**, 485-494.
- Briffa, K.R., V.V. Shishov, T.M. Melvin, E.A. Vaganov, H. Grudd, R.M. Hantemirov, M. Eronen, and M.M. Naurzbaev, 2008:** Trends in recent temperature and radial tree growth spanning 2000 years across northwest Eurasia. *Philosophical Transactions of the Royal Society B*, **363(1501)**, 2271-2284.
- Brink, V.C., 1959:** A directional change in the subalpine forest-heath ecotone in Garibaldi Park, British Columbia. *Ecology*, **40(1)**, 10-16.
- Brisson, J., S. de Blois, and C. Lavoie, 2010:** Roadside as invasion pathway for common reed (*Phragmites australis*). *Invasive Plant Science and Management*, **3(4)**, 506-514.
- Brittain, C., R. Bommarco, M. Vighi, S. Barmaz, J. Settele, and S.G. Potts, 2010a:** The impact of an insecticide on insect flower visitation and pollination in an agricultural landscape. *Agricultural and Forest Entomology*, **12(3)**, 259-266.
- Brittain, C.A., M. Vighi, R. Bommarco, J. Settele, and S.G. Potts, 2010b:** Impacts of a pesticide on pollinator species richness at different spatial scales. *Basic and Applied Ecology*, **11(2)**, 106-115.
- Britton, A.J., C.M. Beale, W. Towers, and R.L. Hewison, 2009:** Biodiversity gains and losses: Evidence for homogenisation of Scottish alpine vegetation. *Biological Conservation*, **142(8)**, 1728-1739.
- Britton, J.R., J. Chucherouset, G.D. Davies, M.J. Godard, and G.H. Copp, 2010:** Non-native fishes and climate change: predicting species responses to warming temperatures in a temperate region. *Freshwater Biology*, **55(5)**, 1130-1141.
- Broadmeadow, M.S.J., D. Ray, and C.J.A. Samuel, 2005:** Climate change and the future for broadleaved tree species in Britain. *Forestry*, **78(2)**, 145-161.
- Broennimann, O., U.A. Treier, H. Muller-Scharer, W. Thuiller, A.T. Peterson, and A. Guisan, 2007:** Evidence of climatic niche shift during biological invasion. *Ecology Letters*, **10(8)**, 701-709.
- Brommer, J.E., A. Lehikoinen, and J. Valkama, 2012:** The breeding ranges of central European and Arctic bird species move poleward. *PLoS One*, **7(9)**, e43648, doi:10.1371/journal.pone.0043648.
- Bronson, D.R., S.T. Gower, M. Tanner, and I. Van Herk, 2009:** Effect of ecosystem warming on boreal black spruce bud burst and shoot growth. *Global Change Biology*, **15(6)**, 1534-1543.
- Brook, B.W., 2008:** Synergies between climate change, extinctions and invasive vertebrates. *Wildlife Research*, **35(3)**, 249-252.
- Brook, B.W. and D.M.J.S. Bowman, 2006:** Postcards from the past: charting the landscape-scale conversion of tropical Australian savanna to closed forest during the 20th century. *Landscape Ecology*, **21(8)**, 1253-1266.
- Brook, B.W., N.S. Sodhi, and C.J.A. Bradshaw, 2008:** Synergies among extinction drivers under global change. *Trends in Ecology & Evolution*, **23(8)**, 453-460.
- Brook, B.W., E.C. Ellis, M.P. Perring, A.W. Mackay, and L. Blomqvist, 2013:** Does the terrestrial biosphere have planetary tipping points? *Trends in Ecology & Evolution*, **28(7)**, 396-401.
- Brouwers, N., J. Mercer, T. Lyons, P. Poot, E. Veneklaas, and G. Hardy, 2012:** Climate and landscape drivers of tree decline in a Mediterranean ecoregion. *Ecology and Evolution*, **3(1)**, 67-79.
- Brouwers, N., G. Matusick, K. Ruthrof, T. Lyons, and G. Hardy, 2013:** Landscape-scale assessment of tree crown dieback following extreme drought and heat in a Mediterranean eucalypt forest ecosystem. *Landscape Ecology*, **28(1)**, 69-80.
- Brovkin, V., L. Boysen, T. Raddatz, V. Gayler, A. Loew, and M. Claussen, 2013:** Evaluation of vegetation cover and land-surface albedo in MPI-ESM CMIP5 simulations. *Journal of Advances in Modeling Earth Systems*, **5(1)**, 48-57.
- Brown, C.D., 2010:** Tree-line dynamics: adding fire to climate change prediction. *Arctic*, **63(4)**, 488-492.
- Brown, L.E., D.M. Hannah, and A.M. Milner, 2007:** Vulnerability of alpine stream biodiversity to shrinking glaciers and snowpacks. *Global Change Biology*, **13(5)**, 958-966.
- Brusca, R.C., J.F. Wiens, W.M. Meyer, J. Eble, K. Franklin, J.T. Overpeck, and M.W., 2013:** Dramatic response to climate change in the Southwest: Robert Whittaker's 1963 Arizona Mountain plant transect revisited. *Ecology and Evolution*, **3(10)**, 3307-3319.
- Bryant, M.D., 2009:** Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of southeast Alaska. *Climatic Change*, **95(1-2)**, 169-193.
- Buckley, J., R.K. Butlin, and J.R. Bridle, 2012:** Evidence for evolutionary change associated with the recent range expansion of the British butterfly, *Aricia agestis*, in response to climate change. *Molecular Ecology*, **21(2)**, 267-280.
- Buckley, L.B., M.C. Urban, M.J. Angilletta, L.G. Crozier, L.J. Rissler, and M.W. Sears, 2010:** Can mechanism inform species' distribution models? *Ecology Letters*, **13(8)**, 1041-1054.
- Buongiorno, J., R. Raunikar, and S. S. A. Zhu, 2011:** Consequences of increasing bioenergy demand on wood and forests: An application of the Global Forest Products Model. *Journal of Forest Economics*, **17(2)**, 214-229.
- Buisson, L. and G. Grenouillet, 2009:** Contrasted impacts of climate change on stream fish assemblages along an environmental gradient. *Diversity and Distributions*, **15(4)**, 613-626.
- Buisson, L., W. Thuiller, S. Lek, P. Lim, and G. Grenouillet, 2008:** Climate change hastens the turnover of stream fish assemblages. *Global Change Biology*, **14(10)**, 2232-2248.
- Buitenwerf, R., W.J. Bond, N. Stevens, and W.W. Trollope, 2012:** Increased tree densities in two South African savannas: > 50 years of data suggests CO₂ as a driver. *Global Change Biology*, **18(2)**, 675-684.
- Bunn, S.E. and A.H. Arthington, 2002:** Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, **30(4)**, 492-507.
- Burgmer, T., H. Hillebrand, and M. Pfenninger, 2007:** Effects of climate-driven temperature changes on the diversity of freshwater macroinvertebrates. *Oecologia*, **151(1)**, 93-103.
- Burkhead, N.M., 2012:** Extinction rates in North American freshwater fishes, 1900-2010. *BioScience*, **62(9)**, 798-808.
- Burkle, L.A., J.C. Marlin, and T.M. Knight, 2013:** Plant-pollinator interactions over 120 Years: loss of species, co-occurrence, and function. *Science*, **339(6127)**, 1611-1615.

- Burrows, M.T., D.S. Schoeman, L.B. Buckley, P. Moore, E.S. Poloczanska, K.M. Brander, C. Brown, J.F. Bruno, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, W. Kiessling, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F.B. Schwing, W.J. Sydeman, and A.J. Richardson, 2011:** The pace of shifting climate in marine and terrestrial ecosystems. *Science*, **334(6056)**, 652-655.
- Burton, O.J., B.L. Phillips, and J.M.J. Travis, 2010:** Trade-offs and the evolution of life-histories during range expansion. *Ecology Letters*, **13(10)**, 1210-1220.
- Bustamante, H.M., L.J. Livo, and C. Carey, 2010:** Effects of temperature and hydric environment on survival of the Panamanian Golden Frog infected with a pathogenic chytrid fungus. *Integrative Zoology*, **5(2)**, 143-153.
- Buswell, J.M., A.T. Moles, and S. Hartley, 2011:** Is rapid evolution common in introduced plant species? *Journal of Ecology*, **99(1)**, 214-224.
- Bütof, A., L.R. von Riedmatten, C.F. Dormann, M. Scherer-Lorenzen, E. Welk, and H. Bruelheide, 2012:** The responses of grassland plants to experimentally simulated climate change depend on land use and region. *Global Change Biology*, **18(1)**, 127-137.
- Butt, N., P.A. de Oliveira, and M.H. Costa, 2011:** Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. *Journal of Geophysical Research: Atmospheres*, **116(D11)**, D11120, doi:10.1029/2010JD015174.
- Cabral, A.C., J.M. Miguel, A.J. Rescia, M.F. Schmitz, and F.D. Pineda, 2009:** Shrub encroachment in Argentinean savannas. *Journal of Vegetation Science*, **14(2)**, 145-152.
- Cadotte, M.W., 2006:** Dispersal and species diversity: a meta-analysis. *American Naturalist*, **167(6)**, 913-924.
- Caesar, J., E. Palin, S. Liddicoat, J. Lowe, E. Burke, A. Pardaens, M. Sanderson, and R. Kahana, 2013:** Response of the HadGEM2 Earth System Model to future greenhouse gas emissions pathways to the year 2300. *Journal of Climate*, **26(10)**, 3275-3284.
- Cahill, A.E., M.E. Aiello-Lammens, M.C. Fisher-Reid, X. Hua, C.J. Karanewsky, H.Y. Ryu, G.C. Sbeglia, F. Spagnolo, J.B. Waldron, O. Warsi, and J.J. Wiens, 2013:** How does climate change cause extinction? *Proceedings of the Royal Society B*, **280(1750)**, 20121890, doi:10.1098/rspb.2012.1890.
- Cailleret, M., M. Nourtier, A. Amm, M. Durand-Gillmann, and H. Davi, 2013:** Drought-induced decline and mortality of silver fir differ among three sites in Southern France. *Annals of Forest Science*, doi:10.1007/s13595-013-0265-0.
- Caissie, D., 2006:** The thermal regime of rivers: a review. *Freshwater Biology*, **51(8)**, 1389-1406.
- Caldow, R.W.G., R.A. Stillman, S.E.A. le V. dit Durell, A.D. West, S. McGrorty, J.D. Goss-Custard, P.J. Wood, and J. Humphreys, 2007:** Benefits to shorebirds from invasion of a non-native shellfish. *Proceedings of the Royal Society B*, **274(1616)**, 1449-1455.
- Cameron, A., 2012:** Refining risk estimates using models. In: *Saving a Million Species: Extinction Risk from Climate Change* [Hannah, L. (ed.)]. Island Press, Washington, DC, USA, pp. 41-72.
- Canadell, J.G. and M.R. Raupach, 2008:** Managing forests for climate change mitigation. *Science*, **320(5882)**, 1456-1457.
- Canadell, J.G., C. Le Quére, M.R. Raupach, C.B. Field, E.T. Buitenhuis, P. Ciais, T.J. Conway, N.P. Gillett, R.A. Houghton, and G. Marland, 2007:** Contributions to accelerating atmospheric CO₂ growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences of the United States of America*, **104(47)**, 18866-18870.
- Canfield, D.E., A.N. Glazer, and P.G. Falkowski, 2010:** The evolution and future of Earth's nitrogen cycle. *Science*, **330(6001)**, 192-196.
- Cannone, N., S. Sgorbati, and M. Guglielmin, 2007:** Unexpected impacts of climate change on alpine vegetation. *Frontiers in Ecology and the Environment*, **5(7)**, 360-364.
- Cannone, N., G. Diolaiuti, M. Guglielmin, and C. Smiraglia, 2008:** Accelerating climate change impacts on alpine glacier forefield ecosystems in the European Alps. *Ecological Applications*, **18(3)**, 637-648.
- Capon, S.J., 2007:** Effects of flooding on seedling emergence from the soil seed bank of a large desert floodplain. *Wetlands*, **27(4)**, 904-914.
- Capon, S.J., L.E. Chambers, R. Mac Nally, R.J. Naiman, P. Davies, N. Marshall, J. Pittock, M. Reid, T. Capon, M. Douglas, J. Catford, D.S. Baldwin, M. Stewardson, J. Roberts, M. Parsons, and S.E. Williams, 2013:** Riparian ecosystems in the 21st century: hotspots for climate change adaptation? *Ecosystems*, **16(3)**, 359-381.
- Carmo, J.B.d., E.R. de Sousa Neto, P.J. Duarte-Neto, J.P.H.B. Ometto, and L.A. Martinelli, 2012:** Conversion of the coastal Atlantic forest to pasture: Consequences for the nitrogen cycle and soil greenhouse gas emissions. *Agriculture, Ecosystems & Environment*, **148(0)**, 37-43.
- Carnicer, J., M. Coll, M. Ninyerola, X. Pons, G. Sanchez, and J. Penuelas, 2011:** Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought. *Proceedings of the National Academy of Sciences of the United States of America*, **108(4)**, 1474-1478.
- Cavagnaro, T.R., R.M. Gleadow, and R.E. Miller, 2011:** Plant nutrient acquisition and utilisation in a high carbon dioxide world. *Functional Plant Biology*, **38(2)**, 87-96.
- CBD, 2012:** *Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters*. CBD Technical Series Series 66, Secretariat of the Convention on Biological Diversity, Montreal, Canada, 152 pp.
- Chapin III, F.S., M. Sturm, M.C. Serreze, J.P. McFadden, J.R. Key, A.H. Lloyd, A.D. McGuire, T.S. Rupp, A.H. Lynch, J.P. Schimel, J. Beringer, W.L. Chapman, H.E. Epstein, E.S. Euskirchen, L.D. Hinzman, G. Jia, C.L. Ping, K.D. Tape, C.D.C. Thompson, D.A. Walker, and J.M. Welker, 2005:** Role of land-surface changes in Arctic summer warming. *Science*, **310(5748)**, 657-660.
- Charru, M., I. Seynave, F. Morneau, and J.D. Bontemps, 2010:** Recent changes in forest productivity: an analysis of national forest inventory data for common beech (*Fagus sylvatica* L.) in north-eastern France. *Forest Ecology and Management*, **260(5)**, 864-874.
- Chaturvedi, R.K., R. Gopalakrishnan, M. Jayaraman, G. Bala, N.V. Joshi, R. Sukumar, and N.H. Ravindranath, 2011:** Impact of climate change on Indian forests: a dynamic vegetation modeling approach. *Mitigation and Adaptation Strategies for Global Change*, **16(2)**, 119-142.
- Cheaih, A., V. Badeau, J. Boe, I. Chuine, C. Delire, E. Dufrière, C. François, E.S. Gritti, M. Legay, C. Pagé, W. Thuiller, N. Viovy, and P. Leadley, 2012:** Climate change impacts on tree ranges: model intercomparison facilitates understanding and quantification of uncertainty. *Ecology Letters*, **15(6)**, 533-544.
- Chen, I.-C., H.J. Shiu, S. Benedick, J.D. Holloway, V.K. Cheye, H.S. Barlow, J.K. Hill, and C.D. Thomas, 2009:** Elevation increases in moth assemblages over 42 years on a tropical mountain. *Proceedings of the National Academy of Sciences of the United States of America*, **106(5)**, 1479-1483.
- Chen, I.-C., J.K. Hill, R. Ohlemüller, D.B. Roy, and C.D. Thomas, 2011:** Rapid range shifts of species associated with high levels of climate warming. *Science*, **333(6045)**, 1024-1026.
- Chessman, B.C., 2009:** Climatic changes and 13-year trends in stream macroinvertebrate assemblages in New South Wales, Australia. *Global Change Biology*, **15(11)**, 2791-2802.
- Chevin, L.M., R. Lande, and G.M. Mace, 2010:** Adaptation, plasticity, and extinction in a changing environment: towards a predictive theory. *PLoS Biology*, **8(4)**, e1000357, doi:10.1371/journal.pbio.1000357.
- Chiba, S. and K. Roy, 2011:** Selectivity of terrestrial gastropod extinctions on an oceanic archipelago and insights into the anthropogenic extinction process. *Proceedings of the National Academy of Sciences of the United States of America*, **108(23)**, 9496-9501.
- Chisholm, R.A., 2010:** Trade-offs between ecosystem services: Water and carbon in a biodiversity hotspot. *Ecological Economics*, **69(10)**, 1973-1987.
- Chmura, D.J., P.D. Anderson, G.T. Howe, C.A. Harrington, J.E. Halofsky, D.L. Peterson, D.C. Shaw, and J.B. St. Clair, 2011:** Forest responses to climate change in the northwestern United States: ecophysiological foundations for adaptive management. *Forest Ecology and Management*, **261(7)**, 1121-1142.
- Choat, B., S. Jansen, T.J. Brodribb, H. Cochard, S. Delzon, R. Bhaskar, S.J. Bucci, T.S. Feild, S.M. Gleason, U.G. Hacke, A.L. Jacobsen, F. Lens, H. Maherali, J. Martinez-Vilalta, S. Mayr, M. Mencuccini, P.J. Mitchell, A. Nardini, J. Pittermann, R.B. Pratt, J.S. Sperry, M. Westoby, I.J. Wright, and A.E. Zanne, 2012:** Global convergence in the vulnerability of forests to drought. *Nature*, **491(7426)**, 752-755.
- Chown, S.L., A.A. Hoffmann, T.N. Kristensen, M.J. Angilletta, N.C. Stenseth, and C. Pertoldi, 2010:** Adapting to climate change: a perspective from evolutionary physiology. *Climate Research*, **43(1-2)**, 3-15.
- Chown, S.L., A.H.L. Huiskes, N.J.M. Gremmen, J.E. Lee, A. Terauds, K. Crosbie, Y. Frenot, K.A. Hughes, S. Imura, K. Kiefer, M. Lebouvier, B. Raymond, M. Tsujimoto, C. Ware, B. van den Vijver, and D.M. Bergstrom, 2012:** Continent-wide risk assessment for the establishment of nonindigenous species in Antarctica. *Proceedings of the National Academy of Sciences of the United States of America*, **109(13)**, 4938-4943.
- Christie, P. and M. Sommerkorn, 2012:** *RaCer: Rapid Assessment of Circum-Arctic Ecosystem Resilience*. WWF Global Arctic Programme, World Wildlife Fund (WWF), Ottawa, Canada, 70 pp.

- Chuine, I., X. Morin, L. Sonie, C. Collin, J. Fabreguettes, D. Degueldre, J.L. Salager, and J. Roy, 2012:** Climate change might increase the invasion potential of the alien C4 grass *Setaria parviflora* (Poaceae) in the Mediterranean Basin. *Diversity and Distributions*, **18(7)**, 661-672.
- Churkina, G., S. Zaehle, J. Hughes, N. Viovy, Y. Chen, M. Jung, B.W. Heumann, N. Ramankutty, M. Heimann, and C. Jones, 2010:** Interactions between nitrogen deposition, land cover conversion, and climate change determine the contemporary carbon balance of Europe. *Biogeosciences*, **7(9)**, 2749-2764.
- Ciais, P., M. Reichstein, N. Viovy, A. Granier, J. Ogee, V. Allard, M. Aubinet, N. Buchmann, C. Bernhofer, A. Carrara, F. Chevallier, N. De Noblet, A.D. Friend, P. Friedlingstein, T. Grunwald, B. Heinesch, P. Keronen, A. Knohl, G. Krinner, D. Loustau, G. Manca, G. Matteucci, F. Miglietta, J.M. Ourcival, D. Papale, K. Pilegaard, S. Rambal, G. Seufert, J.F. Soussana, M.J. Sanz, E.D. Schulze, T. Vesala, and R. Valentini, 2005:** Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, **437(7058)**, 529-533.
- Ciais, P., M.J. Schelhaas, S. Zaehle, L. Piao, A. Cescatti, J. Liski, S. Luysaert, G. Le-Maire, E.D. Schulze, O. Bouriaud, A. Freibauer, R. Valentini, and G.J. Nabuurs, 2008:** Carbon accumulation in European forests. *Nature Geoscience*, **1(7)**, 425-429.
- Clark, C.M. and D. Tilman, 2008:** Loss of plant species after chronic low-level nitrogen deposition to prairie grasslands. *Nature*, **451(7179)**, 712-715.
- Clark, D.A., S.C. Piper, C.D. Keeling, and D.B. Clark, 2003:** Tropical rain forest tree growth and atmospheric carbon dynamics linked to interannual temperature variation during 1984-2000. *Proceedings of the National Academy of Sciences of the United States of America*, **100(10)**, 5852-5857.
- Clark, J.S., 1998:** Why trees migrate so fast: confronting theory with dispersal biology and the paleorecord. *American Naturalist*, **152(2)**, 204-224.
- Clark, P.U., A.S. Dyke, J.D. Shakun, A.E. Carlson, J. Clark, B. Wohlfarth, J.X. Mitrovica, S.W. Hostetler, and A.M. McCabe, 2009:** The Last Glacial Maximum. *Science*, **325(5941)**, 710-714.
- Clarke, H., C. Lucas, and P. Smith, 2013:** Changes in Australian fire weather between 1973 and 2010. *International Journal of Climatology*, **33(4)**, 931-944.
- Claussen, M., 2009:** Late Quaternary vegetation-climate feedbacks. *Climate of the Past*, **5(2)**, 203-216.
- Claussen, M., K. Selent, V. Brovkin, T. Raddatz, and V. Gayler, 2013:** Impact of CO₂ and climate on Last Glacial Maximum vegetation – a factor separation. *Biogeosciences*, **10(6)**, 3593-3604.
- Clavero, M., D. Villero, and L. Brotons, 2011:** Climate change or land use dynamics: Do we know what climate change indicators indicate? *PLoS One*, **6(4)**, e18581, doi:10.1371/journal.pone.0018581.
- Cleland, E. and W.S. Harpole, 2010:** Nitrogen enrichment and plant communities. *Annals of the New York Academy of Sciences*, **1195(1)**, 46-61.
- Cleland, E.E., I. Chuine, A. Menzel, H.A. Mooney, and M.D. Schwartz, 2007:** Shifting plant phenology in response to global change. *Trends in Ecology & Evolution*, **22(7)**, 357-365.
- Cleland, E.E., J.M. Allen, T.M. Crimmins, J.A. Dunne, S. Pau, S. Travers, E.S. Zavaleta, and E.M. Wolkovich, 2012:** Phenological tracking enables positive species responses to climate change. *Ecology*, **93(8)**, 1765-1771.
- Clements, D.R. and A. Ditommaso, 2011:** Climate change and weed adaptation: can evolution of invasive plants lead to greater range expansion than forecasted? *Weed Research*, **51(3)**, 227-240.
- Cobben, M.M.P., J. Verboom, P.F.M. Opdam, R.F. Hoekstra, R. Jochem, and M.J.M. Smulders, 2012:** Wrong place, wrong time: climate change-induced range shift across fragmented habitat causes maladaptation and declined population size in a modelled bird species. *Global Change Biology*, **18(8)**, 2419-2428.
- Cochrane, M.A., 2003:** Fire science for rainforests. *Nature*, **421**, 913-919.
- Cochrane, M.A. and C.P. Barber, 2009:** Climate change, human land use and future fires in the Amazon. *Global Change Biology*, **15(3)**, 601-612.
- Cole, J.J., Y.T. Prairie, N.F. Caraco, W.H. McDowell, L.J. Tranvik, R.G. Striegl, C.M. Duarte, P. Kortelainen, J.A. Downing, J.J. Middelburg, and J. Melack, 2007:** Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. *Ecosystems*, **10(1)**, 171-184.
- Collatz, M.H., M. Ribbas-Carbo, and J.A. Berry, 1992:** Coupled photosynthesis – stomatal conductances model for leaves of C₄ plants. *Australian Journal of Plant Physiology*, **19**, 519-538.
- Collins, J.P., 2010:** Amphibian decline and extinction: what we know and what we need to learn. *Diseases of Aquatic Organisms*, **92(2-3)**, 93-99.
- Colls, A., N. Ash, and N. Ikkala, 2009:** *Ecosystem-based Adaptation: A Natural Response to Climate Change*. International Union for Conservation of Nature and Natural Resources (IUCN), Gland, Switzerland, 16 pp.
- Colwell, R.K., G. Brehm, C.L. Cardelus, A.C. Gilman, and J.T. Longino, 2008:** Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. *Science*, **322(5899)**, 258-261.
- Comte, L. and G. Grenouillet, 2013:** Do stream fish track climate change? Assessing distribution shifts in recent decades. *Ecography*, **36(11)**, 1236-1246.
- Comte, L., L. Buisson, M. Daufresne, and G. Grenouillet, 2013:** Climate-induced changes in the distribution of freshwater fish: observed and predicted trends. *Freshwater Biology*, **58(4)**, 625-639.
- Conlisk, E., D. Lawson, A.D. Syphard, J. Franklin, L. Flint, A. Flint, and H.M. Regan, 2012:** The roles of dispersal, fecundity, and predation in the population persistence of an oak (*Quercus engelmannii*) under global change. *PLoS One*, **7(5)**, e36391, doi:10.1371/journal.pone.0036391.
- Connell, J.H., 1978:** Diversity in tropical rain forests and coral reefs. *Science*, **199(4335)**, 1302-1310.
- Cook, B.I., E.R. Cook, P.C. Huth, J.E. Thompson, A. Forster, and D. Smiley, 2008:** A cross-taxa phenological dataset from Mohonk Lake, NY and its relationship to climate. *International Journal of Climatology*, **28(10)**, 1369-1383.
- Cook, B.I., E.M. Wolkovich, T.J. Davies, T.R. Ault, J.L. Betancourt, J.M. Allen, K. Bolmgren, E.E. Cleland, T.M. Crimmins, N.J.B. Kraft, L.T. Lancaster, S.J. Mazer, G.J. McCabe, B.J. McGill, C. Parmesan, S. Pau, J. Regetz, N. Salamin, M.D. Schwartz, and S.E. Travers, 2012a:** Sensitivity of spring phenology to warming across temporal and spatial climate gradients in two independent databases. *Ecosystems*, **15(8)**, 1283-1294.
- Cook, B.I., E.M. Wolkovich, and C. Parmesan, 2012b:** Divergent responses to spring and winter warming drive community level flowering trends. *Proceedings of the National Academy of Sciences of the United States of America*, **109(23)**, 9000-9005.
- Cooper, O.R., D.D. Parrish, A. Stohl, M. Trainer, P. Nedelec, V. Thouret, J.P. Cammas, S.J. Oltmans, B.J. Johnson, D. Tarasick, T. Leblanc, I.S. McDermid, D. Jaffe, R. Gao, S. Stith, T. Ryerson, K. Aikin, T. Campos, A. Weinheimer, and A.M. Avery, 2010:** Increasing springtime ozone mixing ratios in the free troposphere over western North America. *Nature*, **463(12)**, 344-348.
- Corlett, R.T., 2011:** Impacts of warming on tropical lowland rainforests. *Trends in Ecology & Evolution*, **26(11)**, 606-613.
- Costa, M.H., S.N.M. Yanagi, P. Souza, A. Ribeiro, and E.J.P. Rocha, 2007:** Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion. *Geophysical Research Letters*, **34(7)**, L07706, doi:10.1029/2007GL029271.
- Cox, P.M., C. Huntingford, and R.J. Harding, 1998:** A canopy conductance and photosynthesis model for use in a GCM land surface scheme. *Journal of Hydrology*, **212-213**, 79-94.
- Cox, P.M., D. Pearson, B.B. Booth, P. Friedlingstein, C. Huntingford, C.D. Jones, and C.M. Luke, 2013:** Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability. *Nature*, **494(7437)**, 341-344.
- Crimmins, S.M., S.Z. Dobrowski, J.A. Greenberg, J.T. Abatzoglou, and A.R. Mynsberge, 2011:** Changes in climatic water balance drive downhill shifts in plant species' optimum elevations. *Science*, **331(6015)**, 324-327.
- Crimmins, T.M., M.A. Crimmins, and C.D. Bertelsen, 2009:** Flowering range changes across an elevation gradient in response to warming summer temperatures. *Global Change Biology*, **15(5)**, 1141-1152.
- Crossman, J., M.N. Fitter, S.K. Oni, P.G. Whitehead, L. Jin, D. Butterfield, H.M. Baulch, and P.J. Dillon, 2013:** Impacts of climate change on hydrology and water quality: future proofing management strategies in the Lake Simcoe watershed, Canada. *Journal of Great Lakes Research*, **39(1)**, 19-32.
- Crous, C.J., S.M. Jacobs, and K.J. Esler, 2012:** Drought-tolerance of an invasive alien tree, *Acacia mearnsii* and two native competitors in fynbos riparian ecotones. *Biological Invasions*, **14(3)**, 619-631.
- Cui, X.F. and H.F. Graf, 2009:** Recent land cover changes on the Tibetan Plateau: a review. *Climatic Change*, **94(1-2)**, 47-61.
- Curran, L.M., S.N. Trigg, A.K. McDonald, D. Astiani, Y.M. Hardiono, P. Siregar, I. Caniago, and E. Kasischke, 2004:** Lowland forest loss in protected areas of Indonesian Borneo. *Science*, **303(5660)**, 1000-1003.
- da Costa, A.C.L., D. Galbraith, S. Almeida, B.T.T. Portela, M. Da Costa, J. De Athaydes Silva Junior, A.P. Braga, P.H.L. De Gonçalves, A.A. De Oliveira, R. Fisher, O.L. Phillips, D.B. Metcalfe, P. Levy, and P. Meir, 2010:** Effect of 7 yr of experimental drought on vegetation dynamics and biomass storage of an eastern Amazonian rainforest. *New Phytologist*, **187(3)**, 579-591.
- Dahm, C.N., M.A. Baker, D.I. Moore, and J.R. Thibault, 2003:** Coupled biogeochemical and hydrological responses of streams and rivers to drought. *Freshwater Biology*, **48(7)**, 1219-1231.

- Dai, F., Z. Su, S. Liu, and G. Liu, 2011:** Temporal variation of soil organic matter content and potential determinants in Tibet, China. *Catena*, **85(3)**, 288-294.
- Dale, V.H., M.L. Tharp, K.O. Lannom, and D.G. Hodges, 2010:** Modeling transient response of forests to climate change. *Science of the Total Environment*, **408(8)**, 1888-1901.
- Danby, R.K., and D.S. Hik, 2007:** Variability, contingency and rapid change in recent subarctic alpine tree line dynamics. *Journal of Ecology*, **95(2)**, 352-363.
- Daniau, A.L., S.P. Harrison, and P.J. Bartlein, 2010:** Fire regimes during the Last Glacial. *Quaternary Science Reviews*, **29(21-22)**, 2918-2930.
- Daniau, A.L., P.J. Bartlein, S.P. Harrison, I.C. Prentice, S. Brewer, P. Friedlingstein, T.I. Harrison-Prentice, J. Inoue, K. Izumi, J.R. Marlon, S. Mooney, M.J. Power, J. Stevenson, W. Tinner, M. Andric, J. Atanassova, H. Behling, M. Black, O. Blarquez, K.J. Brown, C. Carcaillet, E.A. Colhoun, D. Colombaroli, B.A.S. Davis, D. D'Costa, J. Dodson, L. Dupont, Z. Eshetu, D.G. Gavin, A. Genries, S. Haberle, D.J. Hallett, G. Hope, S.P. Horn, T.G. Kassa, F. Katamura, L.M. Kennedy, P. Kershaw, S. Krivonogov, C. Long, D. Magri, E. Marinova, G.M. McKenzie, P.I. Moreno, P. Moss, F.H. Neumann, E. Norstrom, C. Paitre, D. Rius, N. Roberts, G.S. Robinson, N. Sasaki, L. Scott, H. Takahara, V. Terwilliger, F. Thevenon, R. Turner, V.G. Valsecchi, B. Vanniere, M. Walsh, N. Williams, and Y. Zhang, 2012:** Predictability of biomass burning in response to climate changes. *Global Biogeochemical Cycles*, **26(4)**, GB4007, doi:10.1029/2011GB004249.
- Daufresne, M. and P. Boet, 2007:** Climate change impacts on structure and diversity of fish communities in rivers. *Global Change Biology*, **13(12)**, 2467-2478.
- Davidson, A.M., M. Jennions, and A.B. Nicotra, 2011:** Do invasive species show higher phenotypic plasticity than native species and, if so, is it adaptive? A meta-analysis. *Ecology Letters*, **14(4)**, 419-431.
- Davidson, E.A. and I.A. Janssens, 2006:** Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, **440**, 165-173.
- Davidson, E.A., A.C. de Araujo, P. Artaxo, J.K. Balch, I.F. Brown, M.M.C. Bustamante, M.T. Coe, R.S. DeFries, M. Keller, M. Longo, J.W. Munger, W. Schroeder, B.S. Soares, C.M. Souza, and S.C. Wofsy, 2012:** The Amazon basin in transition. *Nature*, **481(7381)**, 321-328.
- Davies, P.M., 2010:** Climate change implications for river restoration in global biodiversity hotspots. *Restoration Ecology*, **18(3)**, 261-268.
- Davin, E.L. and N. de Noblet-Ducoudre, 2010:** Climatic impact of global-scale deforestation: radiative versus nonradiative processes. *Journal of Climate*, **23(1)**, 97-112.
- Davin, E.L., N. de Noblet-Ducoudre, and P. Friedlingstein, 2007:** Impact of land cover change on surface climate: relevance of the radiative forcing concept. *Geophysical Research Letters*, **34(13)**, L13702, doi:10.1029/2007GL029678.
- Davis, C.C., C.G. Willis, R.B. Primack, and A.J. Miller-Rushing, 2010:** The importance of phylogeny to the study of phenological response to global climate change. *Philosophical Transactions of the Royal Society B*, **365(1555)**, 3201-3213.
- Davis, J.L., S. Lake, and R. Thompson, 2010:** Freshwater biodiversity and climate change. In: *Managing Climate Change: Papers from the Greenhouse 2009 Conference* [Jubb, I., P. Holper, and W. Cai (eds.)]. Commonwealth Scientific and Industrial Research Organisation (CSIRO) Publishing, Collingwood, Australia, pp. 73-84.
- Dawes, M.A., S. Hättenschwiler, P. Bebi, F. Hagedorn, I.T. Handa, C. Körner, and C. Rixen, 2011:** Species-specific tree growth responses to 9 years of CO₂ enrichment at the alpine treeline. *Journal of Ecology*, **99(2)**, 383-394.
- Dawson, T.P., S.T. Jackson, J.I. House, I.C. Prentice, and G.M. Mace, 2011:** Beyond predictions: biodiversity conservation in a changing climate. *Science*, **332(6025)**, 53-58.
- de Jong, R., S. de Bruin, A. de Wit, M.E. Schaepman, and D.L. Dent, 2011:** Analysis of monotonic greening and browning trends from global NDVI time-series. *Remote Sensing of Environment*, **115(2)**, 692-702.
- De Kauwe, M.G., B.E. Medlyn, S. Zaehle, A.P. Walker, M.C. Dietze, T. Hickler, A.K. Jain, Y. Luo, W.J. Parton, C. Prentice, B. Smith, P.E. Thornton, S. Wang, Y.-P. Wang, D. Wårlind, E.S. Weng, K.Y. Crous, D.S. Ellsworth, P.J. Hanson, H. Seok-Kim, J.M. Warren, R. Oren, and R.J. Norby, 2013:** Forest water use and water use efficiency at elevated CO₂: a model-data intercomparison at two contrasting temperate forest FACE sites. *Global Change Biology*, **19(6)**, 1759-1779.
- De Michele, C., F. Accatino, R. Vezzoli, and R.J. Scholes, 2011:** Savanna domain in the herbivores-fire parameter space exploiting a tree-grass-soil water dynamic model. *Journal of Theoretical Biology*, **289**, 74-82.
- de Noblet-Ducoudre, N., J.P. Boisier, A. Pitman, G.B. Bonan, V. Brovkin, F. Cruz, C. Delire, V. Gayler, B.J.J.M. van den Hurk, P.J. Lawrence, M.K. van der Molen, C. Muller, C.H. Reick, B.J. Stangens, and A. Voldoire, 2012:** Determining robust impacts of land-use-induced land cover changes on surface climate over North America and Eurasia: results from the first set of LUCID experiments. *Journal of Climate*, **25(9)**, 3261-3281.
- de Torres Curth, M.I., L. Ghermandi, and C. Biscayart, 2012:** Are *Fabiana imbricata* shrublands advancing over northwestern Patagonian grasslands? A population dynamics study involving fire and precipitation. *Journal of Arid Environments*, **83**, 78-85.
- de Vries, W. and M. Posch, 2011:** Modelling the impact of nitrogen deposition, climate change and nutrient limitations on tree carbon sequestration in Europe for the period 1900-2050. *Environmental Pollution*, **159(10)**, 2289-2299.
- DeFries, R.S., T. Rudel, M. Uriarte, and M. Hansen, 2010:** Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nature Geoscience*, **3(3)**, 178-181.
- Delire, C., N. de Noblet-Ducoudre, A. Sima, and I. Gouirand, 2011:** Vegetation dynamics enhancing long-term climate variability confirmed by two models. *Journal of Climate*, **24(9)**, 2238-2257.
- Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P.L. da Silva Dias, S.C. Wofsy, and X. Zhang, 2007:** Couplings between changes in the climate system and biogeochemistry. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA., pp. 499-587.
- Dentener, F., T. Keating, and H. Akimoto (eds.), 2010:** *Hemispheric Transport of Air Pollution 2010: Part A – Ozone and Particulate Matter*. United Nations Economic Commission for Europe (UNECE) Air Pollution Series Studies No. 17, United Nations, New York, NY, USA and Geneva, Switzerland, 304 pp.
- DeRose, R.J. and J.N. Long, 2012:** Drought-driven disturbance history characterizes a southern Rocky Mountain subalpine forest. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **42(9)**, 1649-1660.
- Deutsch, C.A., J.J. Tewksbury, R.B. Huey, K.S. Sheldon, C.K. Ghalambor, D.C. Haak, and P.R. Martin, 2008:** Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of Sciences of the United States of America*, **105(18)**, 6668-6672.
- Devi, N., F. Hagedorn, P. Moiseev, H. Bugmann, S. Shiyatov, V. Mazepa, and A. Rigling, 2008:** Expanding forests and changing growth forms of Siberian larch at the Polar Urals treeline during the 20th century. *Global Change Biology*, **14(7)**, 1581-1591.
- Devictor, V., C. van Swaay, T. Brereton, L. Brotons, D. Chamberlain, J. Heliola, S. Herrando, R. Julliard, M. Kuussaari, A. Lindstrom, J. Reif, D.B. Roy, O. Schweiger, J. Settele, C. Stefanescu, A. Van Strien, C. Van Turnhout, Z. Vermouzek, M. Wallis DeVries, I. Wynhoff, and F. Jiguet, 2012:** Differences in the climatic debts of birds and butterflies at a continental scale. *Nature Climate Change*, **2(2)**, 121-124.
- Dial, R.J., E.E. Berg, K. Timm, A. McMahon, and J. Geck, 2007:** Changes in the alpine forest-tundra ecotone commensurate with recent warming in southcentral Alaska: evidence from orthophotos and field plots. *Journal of Geophysical Research: Biogeosciences*, **112(G4)**, G04015, doi:10.1029/2007JG000453.
- Dieleman, W.I.J., S. Vicca, F.A. Dijkstra, F. Hagedorn, M.J. Hovenden, K.S. Larsen, J.A. Morgan, A. Volder, C. Beier, J.S. Dukes, J. King, S. Leuzinger, S. Linder, Y. Luo, R. Oren, P. De Angelis, D. Tingey, M.R. Hoosbeek, and I.A. Janssens, 2012:** Simple additive effects are rare: a quantitative review of plant biomass and soil process responses to combined manipulations of CO₂ and temperature. *Global Change Biology*, **18(9)**, 2681-2693.
- Diez, J.M., C.M. D'Antonio, J.S. Dukes, E.D. Grosholz, J.D. Olden, C.J.B. Sorte, D.M. Blumenthal, B.A. Bradley, R. Early, I. Ibanez, S.J. Jones, J.J. Lawler, and L.P. Miller, 2012:** Will extreme climatic events facilitate biological invasions? *Frontiers in Ecology and the Environment*, **10(5)**, 249-257.
- Diffenbaugh, N.S. and F. Giorgi, 2012:** Climate change hotspots in the CMIP5 global climate model ensemble. *Climatic Change*, **114(3-4)**, 813-822.
- Diffenbaugh, N.S., J.S. Pal, R.J. Trapp, and F. Giorgi, 2005:** Fine-scale processes regulate the response of extreme events to global climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **102(44)**, 15774-15778.
- Dise, N.B., 2009:** Peatland response to global change. *Science*, **326(5954)**, 810-811.
- Doak, D.F. and W.F. Morris, 2010:** Demographic compensation and tipping points in climate-induced range shifts. *Nature*, **467(7318)**, 959-962.
- Dobrowski, S.Z., J. Abatzoglou, A.K. Swanson, J.A. Greenberg, A.R. Mynsberge, Z.A. Holden, and M.K. Schwartz, 2013:** The climate velocity of the contiguous United States during the 20th century. *Global Change Biology*, **19(1)**, 241-251.

- Dohrenbusch, A.** and A. Bolte, 2007: Forest plantations. In: *Wood Production, Wood Technology and Biotechnological Impacts* [Kües, U. (ed.)]. Universitätsverlag Göttingen, Göttingen, Germany, pp. 73-83.
- Donnelly, A., A. Caffarra, C.T. Kelleher, B.F. O'Neill, E. Diskin, A. Pletsers, H. Proctor, R. Stirnemann, J. O'Halloran, J. Penuelas, T.R. Hodkinson, and T.H. Sparks,** 2012: Surviving in a warmer world: environmental and genetic responses. *Climate Research*, **53(3)**, 245-262.
- Donohue, R.J., T.R. McVicar, M.L. Roderick, and G.D. Farquhar,** 2013: Impact of CO₂ fertilization on maximum foliage cover across the globe's warm, arid environments. *Geophysical Research Letters*, **40**, 3031-3035.
- Doughty, C.E.** and M.L. Goulden, 2008: Are tropical forests near a high temperature threshold? *Journal of Geophysical Research: Biogeosciences*, **113(G1)**, G00B07, doi:10.1029/2007JG000632.
- Doughty, C.E., C.B. Field, and A.M.S. McMillan,** 2011: Can crop albedo be increased through modification of leaf trichomes, and could this cool the regional climate? *Climatic Change*, **104(2)**, 379-387.
- Douville, H., A. Ribes, B. Decharme, R. Alkama, and J. Sheffield,** 2013: Anthropogenic influence on multidecadal changes in reconstructed global evapotranspiration. *Nature Climate Change*, **3(1)**, 59-62.
- Doxford, S.W.** and R.P. Freckleton, 2012: Changes in the large-scale distribution of plants: extinction, colonisation and the effects of climate. *Journal of Ecology*, **100(2)**, 519-529.
- Drewitt, A.L.** and R.H.W. Langston, 2006: Assessing the impacts of wind farms on birds. *Ibis*, **148**, 29-42.
- Dudgeon, D., A.H. Arthington, M.O. Gessner, Z.I. Kawabata, D.J. Knowler, C. Leveque, R.J. Naiman, A.H. Prieur-Richard, D. Soto, M.L.J. Stiassny, and C.A. Sullivan,** 2006: Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews*, **81(2)**, 163-182.
- Dukes, J.S., J. Pontius, D. Orwig, J.R. Garnas, V.L. Rodgers, N. Brazeel, B. Cooke, K.A. Theoharides, E.E. Stange, R. Harrington, J. Ehrenfeld, J. Gurevitch, M. Lerda, K. Stinson, R. Wick, and M. Ayres,** 2009: Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: what can we predict? *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **39(2)**, 231-248.
- Dulamsuren, C., M. Hauck, S. Nyambayar, M. Bader, D. Osokhjargal, S. Oyungerel, and C. Leuschner,** 2009: Performance of Siberian elm (*Ulmus pumila*) on steppe slopes of the northern Mongolian mountain taiga: drought stress and herbivory in mature trees. *Environmental and Experimental Botany*, **66(1)**, 18-24.
- Dullinger, S., A. Gatteringer, W. Thuiller, D. Moser, N.E. Zimmermann, A. Guisan, W. Willner, C. Plutzer, M. Leitner, T. Mang, M. Caccianiga, T. Dirnbock, S. Ertl, A. Ischer, J. Lenoir, J.C. Svenning, A. Psomas, D.R. Schmatz, U. Silc, P. Vittoz, and K. Hulber,** 2012: Extinction debt of high-mountain plants under twenty-first-century climate change. *Nature Climate Change*, **2(8)**, 619-622.
- Dunlop, M., D.W. Hilbert, S. Ferrier, A. House, A. Liedloff, S.M. Prober, A. Smyth, T.G. Martin, T. Harwood, K.J. Williams, C. Fletcher, and H. Murphy,** 2012: *The Implications of Climate Change for Biodiversity Conservation and the National Reserve System: Final Synthesis*. Canberra, ACT, Australia, 80 pp.
- Dunn, R.R., N.C. Harris, R.K. Colwell, L.P. Koh, and N.S. Sodhi,** 2009: The sixth mass coextinction: are most endangered species parasites and mutualists? *Proceedings of the Royal Society B*, **276(1670)**, 3037-3045.
- Durance, I.** and S.J. Ormerod, 2007: Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology*, **13(5)**, 942-957.
- Eamus, D.** and A.R. Palmer, 2007: Is climate change a possible explanation for woody thickening in arid and semi-arid regions? *International Journal of Ecology*, **2007**, 37364, doi:10.1155/2007/37364.
- Eastaugh, C.S., E. Potzelsberger, and H. Hasenauer,** 2011: Assessing the impacts of climate change and nitrogen deposition on Norway spruce (*Picea abies* L. Karst) growth in Austria with BIOME-BGC. *Tree Physiology*, **31(3)**, 262-274.
- Edburg, S.L., J.A. Hicke, P.D. Brooks, E.G. Pendall, B.E. Ewers, U. Norton, D. Gochis, E.D. Gutmann, and A.J.H. Meddens,** 2012: Cascading impacts of bark beetle-caused tree mortality on coupled biogeophysical and biogeochemical processes. *Frontiers in Ecology and the Environment*, **10(8)**, 416-424.
- Eggermont, H., D. Verschuren, L. Audenaert, L. Lens, J. Russell, G. Klaassen, and O. Heiri,** 2010: Limnological and ecological sensitivity of Rwenzori mountain lakes to climate warming. *Hydrobiologia*, **648(1)**, 123-142.
- Eisenhauer, N., S. Cesarz, R. Koller, K. Worm, and P.B. Reich,** 2012: Global change belowground: impacts of elevated CO₂, nitrogen, and summer drought on soil food webs and biodiversity. *Global Change Biology*, **18(2)**, 435-447.
- Eliasch, J.,** 2008: *Climate Change: Financing Global Forests – The Eliasch Review*. Earthscan, Abingdon, UK and New York, NY, USA, 288 pp.
- Elith, J.** and J.R. Leathwick, 2009: Species distribution models: ecological explanation and prediction across space and time. *Annual Review of Ecology Evolution and Systematics*, **40**, 677-697.
- Ellery, W.N., R.J. Scholes, and M.T. Mentis,** 1991: An initial approach to predicting the sensitivity of the South African grassland biome to climate change. *South African Journal of Science*, **87**, 499-503.
- Elmendorf, S.C., G.H.R. Henry, R.D. Hollister, R.G. Bjork, N. Boulanger-Lapointe, E.J. Cooper, J.H.C. Cornelissen, T.A. Day, E. Dorrepaal, T.G. Elumeeva, M. Gill, W.A. Gould, J. Harte, D.S. Hik, A. Hofgaard, D.R. Johnson, J.F. Johnstone, I.S. Jonsdottir, J.C. Jorgenson, K. Klanderud, J.A. Klein, S. Koh, G. Kudo, M. Lara, E. Levesque, B. Magnusson, J.L. May, J.A. Mercado-Diaz, A. Michelsen, U. Molau, I.H. Myers-Smith, S.F. Oberbauer, V.G. Onipchenko, C. Rixen, N. Martin Schmidt, G.R. Shaver, M.J. Spasojevic, o.E. orhallsdottir, A. Tolvanen, T. Troxler, C.E. Tweedie, S. Villareal, C.-H. Wahren, X. Walker, P.J. Webber, J.M. Welker, and S. Wipf,** 2012: Plot-scale evidence of tundra vegetation change and links to recent summer warming. *Nature Climate Change*, **2(6)**, 453-457.
- Elser, J.J., M.E.S. Bracken, E.E. Cleland, D.S. Gruner, W.S. Harpole, H. Hillebrand, J.T. Ngai, E.W. Seabloom, J.B. Shurin, and J.E. Smith,** 2007: Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecology Letters*, **10**, 1135-1142.
- Elser, J.J., T. Andersen, J.S. Baron, A.K. Bergström, M. Jansson, M. Kyle, K.R. Nydick, L. Steger, and D.O. Hessen,** 2009: Shifts in lake N:P stoichiometry and nutrient limitation driven by atmospheric nitrogen deposition. *Science*, **326(5954)**, 835-837.
- Emmett, B.A., C. Beier, M. Estiarte, A. Tietema, H.L. Kristensen, D. Williams, J. Penuelas, I. Schmidt, and A. Sowerby,** 2004: The response of soil processes to climate change: results from manipulation studies of shrublands across an environmental gradient. *Ecosystems*, **7(6)**, 625-637.
- Engler, R., C.F. Randin, W. Thuiller, S. Dullinger, N.E. Zimmermann, M.B. Araujo, P.B. Pearman, G. Le Lay, C. Peidallu, C.H. Albert, P. Choler, G. Coldea, S. De Lamo, T. Dirnbock, J.C. Gegout, D. Gomez-Garcia, J.A. Grytnes, E. Heegaard, F. Hoistad, D. Nogues-Bravo, S. Normand, M. Puscas, M.T. Sebastia, A. Stanisci, J.P. Theurillat, M.R. Trivedi, P. Vittoz, and A. Guisan,** 2011: 21st century climate change threatens mountain flora unequally across Europe. *Global Change Biology*, **17(7)**, 2330-2341.
- Enquist, B.J.** and C.A.F. Enquist, 2011: Long-term change within a Neotropical forest: assessing differential functional and floristic responses to disturbance and drought. *Global Change Biology*, **17(3)**, 1408-1424.
- Epstein, H., J. Kaplan, H. Lischke, and Q. Yu,** 2007: Simulating future changes in arctic tundra and sub-arctic vegetation. *Computing in Science and Engineering*, **9**, 12-23.
- Epstein, H.E., D.A. Walker, M. K. Reynolds, G. J. Jia, and A. M. Kelley,** 2008: Phytomass patterns across a temperature gradient of the North American arctic tundra. *Journal of Geophysical Research: Biogeosciences*, **113(G3)**, G03S02, doi:10.1029/2007JG000555.
- Erlandsson, M., I. Buffam, J. Folster, H. Laudon, J. Temnerud, G.A. Weyhenmeyer, and K. Bishop,** 2008: Thirty-five years of synchrony in the organic matter concentrations of Swedish rivers explained by variation in flow and sulphate. *Global Change Biology*, **14(5)**, 1191-1198.
- Ersikine, P.D., D. Lamb, and M. Bristow,** 2006: Tree species diversity and ecosystem function: can tropical multi-species plantations generate greater productivity? *Forest Ecology and Management*, **233(2-3)**, 205-210.
- Essi, F., S. Dullinger, D. Moser, W. Rabitsch, and I. Kleinbauer,** 2012: Vulnerability of mires under climate change: implications for nature conservation and climate change adaptation. *Biodiversity and Conservation*, **21(3)**, 655-669.
- EU Council,** 1992: *Council Directive 92/43/EEC of 21 May 1992 on the Conservation of Natural Habitats and of Wild Fauna and Flora*. The Council of the European Communities, Brussels, Belgium, 66 pp.
- Euskirchen, E.S., A.D. McGuire, F.S. Chapin III, S. Yi, and C.C. Thompson,** 2009: Changes in vegetation in northern Alaska under scenarios of climate change, 2003-2100: implications for climate feedbacks. *Ecological Applications*, **19(4)**, 1022-1043.
- Evans, C.D., D.T. Monteith, and D.M. Cooper,** 2005: Long-term increases in surface water dissolved organic carbon: observations, possible causes and environmental impacts. *Environmental Pollution*, **137(1)**, 55-71.
- Eycott, A.E., G.B. Stewart, L.M. Buyung-Ali, D.E. Bowler, K. Watts, and A.S. Pullin,** 2012: A meta-analysis on the impact of different matrix structures on species movement rates. *Landscape Ecology*, **27(9)**, 1263-1278.

- Fahey, T.J., 1998: Recent changes in an upland forest in South-Central New York. *Journal of the Torrey Botanical Society*, **125**(1), 51-59.
- Fall, S., D. Niyogi, A. Gluhovsky, R.A. Pielke, E. Kalnay, and G. Rochon, 2010: Impacts of land use land cover on temperature trends over the continental United States: assessment using the North American Regional Reanalysis. *International Journal of Climatology*, **30**(13), 1980-1993.
- Falloon, P.D., R. Dankers, R.A. Betts, C.D. Jones, B.B.B. Booth, and F.H. Lambert, 2012: Role of vegetation change in future climate under the A1B scenario and a climate stabilisation scenario, using the HadCM3C earth systems model. *Biogeosciences*, **9**(11), 4739-4756.
- FAO, 2005: *Global Forest Resources Assessment 2005*. FAO Forestry Paper No. 147, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 350 pp.
- FAO, 2010: *Global Forest Resources Assessment 2010*. FAO Forestry Paper No. 163, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 340 pp.
- Farquhar, G.D., S. von Caemmerer, and J.A. Berry, 1980: A biochemical model of photosynthetic CO₂ assimilation in leaves of C₃ species. *Planta*, **149**, 78-90.
- Fauset, S., T.R. Baker, S.L. Lewis, T.R. Feldpausch, K. Affum-Baffoe, E.G. Foli, K.C. Hamer, and M.D. Swaine, 2012: Drought-induced shifts in the floristic and functional composition of tropical forests in Ghana. *Ecology Letters*, **15**(10), 1120-1129.
- Fay, P.A., J.D. Carlisle, A.K. Knapp, J.M. Blair, and S.L. Collins, 2003: Productivity responses to altered rainfall patterns in a C₄-dominated grassland. *Oecologia*, **137**(2), 245-251.
- Feeley, K.J. and E.M. Rehm, 2012: Amazon's vulnerability to climate change heightened by deforestation and man-made dispersal barriers. *Global Change Biology*, **18**(12), 3606-3614.
- Fellows, A.W. and M.L. Goulden, 2012: Rapid vegetation redistribution in Southern California during the early 2000s drought. *Journal of Geophysical Research: Biogeosciences*, **117**(G3), G03025, doi:10.1029/2012JG002044.
- Fensham, R.J., R.J. Fairfax, and D.P. Ward, 2009: Drought-induced tree death in savanna. *Global Change Biology*, **15**, 380-387.
- Fensham, R.J., R.J. Fairfax, and J.M. Dwyer, 2012: Potential aboveground biomass in drought-prone forest used for rangeland pastoralism. *Ecological Applications*, **22**(3), 894-908.
- Fensholt, R., T. Langanke, K. Rasmussen, A. Reenberg, S.D. Prince, C. Tucker, B. Scholes, Q.B. Le, A. Bondeau, R. Eastman, H. Epstein, A.E. Gaughan, U. Hellden, C. Mbow, L. Olsson, J. Paruelo, C. Schweitzer, J. Seaquist, and K. Wessels, 2012: Greenness in semi-arid areas across the globe 1981-2007 – an Earth Observing Satellite based analysis of trends and drivers. *Remote Sensing of Environment*, **121**, 144-158.
- Ferriere, R. and S. Legendre, 2013: Eco-evolutionary feedbacks, adaptive dynamics and evolutionary rescue theory. *Philosophical Transactions of the Royal Society B*, **368**(1610), 20120081, doi:10.1098/rstb.2012.0404.
- Ficke, A.D., C.A. Myrick, and L.J. Hansen, 2007: Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries*, **17**(4), 581-613.
- Field, C.B., D.B. Lobell, H.A. Peters, and N.R. Chiariello, 2007: Feedbacks of terrestrial ecosystems to climate change. *Annual Review of Environment and Resources*, **32**, 1-29, doi:10.1146/annurev.energy.32.053006.141119.
- Findell, K.L., E. Shevliakova, P.C.D. Milly, and R.J. Stouffer, 2007: Modeled impact of anthropogenic land cover change on climate. *Journal of Climate*, **20**(14), 3621-3634.
- Finn, D.S., K. Khamis, and A.M. Milner, 2013: Loss of small glaciers will diminish beta diversity in Pyrenean streams at two levels of biological organization. *Global Ecology and Biogeography*, **22**(1), 40-51.
- Finzi, A.C., R.J. Norby, C. Calfapietra, A. Gallet-Budynek, B. Gielen, W.E. Holmes, M.R. Hoosbeek, C.M. Iversen, R.B. Jackson, M.E. Kubiske, J. Ledford, M. Liberloo, R. Oren, A. Polle, S. Pritchard, D.R. Zak, W.H. Schlesinger, and R. Ceulemans, 2007: Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO₂. *Proceedings of the National Academy of Sciences of the United States of America*, **104**(35), 14014-14019.
- Fiorese, G. and G. Guariso, 2013: Modeling the role of forests in a regional carbon mitigation plan. *Renewable Energy*, **52**, 175-182.
- Fischer, J. and D.B. Lindenmayer, 2007: Landscape modification and habitat fragmentation: a synthesis. *Global Ecology and Biogeography*, **16**(3), 265-280.
- Fischlin, A., G.F. Midgley, J.T. Price, R. Leemans, B. Gopal, C. Turley, M.D.A. Rounsevell, O.P. Dube, J. Tarazona, and A.A. Velichko, 2007: Ecosystems, their properties, goods, and services. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 211-272.
- Fisher, J.B., G. Hurtt, R.Q. Thomas, and J.Q. Chambers, 2008: Clustered disturbances lead to bias in large-scale estimates based on forest sample plots. *Ecology Letters*, **11**(6), 554-563.
- Fisher, R., N. McDowell, D. Purves, P. Moorcroft, S. Sitch, P. Cox, C. Huntingford, P. Meir, and F. Ian Woodward, 2010: Assessing uncertainties in a second-generation dynamic vegetation model caused by ecological scale limitations. *New Phytologist*, **187**(3), 666-681.
- FLUXNET, 2012: *Historical Site Status*. fluxnet.ornl.gov/site_status.
- Foden, W.B., S.H.M. Butchart, S.N. Stuart, J.C. Vie, H.R. Akcakaya, A. Angulo, L.M. DeVantier, A. Gutsche, E. Turak, L. Cao, S.D. Donner, V. Katariya, R. Bernard, R.A. Holland, A.F. Hughes, S.E. O'Hanlon, S.T. Garnett, C.H. Sekercioglu, and G.M. Mace, 2013: Identifying the world's most climate change vulnerable species: a systematic trait-based assessment of all birds, amphibians and corals. *PLoS One*, **8**(6), e65427, doi:10.1371/journal.pone.0065427.
- Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C.S. Holling, 2004: Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology Evolution and Systematics*, **35**, 557-581.
- Forbes, B.C., M.M. Fauria, and P. Zetterberg, 2010: Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows. *Global Change Biology*, **16**(5), 1542-1554.
- Fordham, D.A., H.R. Akcakaya, M.B. Araujo, J. Elith, D.A. Keith, R. Pearson, T.D. Auld, C. Mellin, J.W. Morgan, T.J. Regan, M. Tozer, M.J. Watts, M. White, B.A. Wintle, C. Yates, and B.W. Brook, 2012: Plant extinction risk under climate change: are forecast range shifts alone a good indicator of species vulnerability to global warming? *Global Change Biology*, **18**(4), 1357-1371.
- Fowler, D., M. Coyle, U. Skiba, M.A. Sutton, J.N. Cape, S. Reis, L.J. Sheppard, A. Jenkins, B. Grizzetti, J.N. Galloway, P. Vitousek, A. Leach, A.F. Bouwman, K. Butterbach-Bahl, F. Dentener, D. Stevenson, M. Amann, and M. Voss, 2013: The global nitrogen cycle in the twenty-first century. *Philosophical Transactions of the Royal Society B*, **368**(1621), 20130164, doi:10.1098/rstb.2013.0164.
- Franklin, J., F.W. Davis, M. Ikegami, A.D. Syphard, L.E. Flint, A.L. Flint, and L. Hannah, 2013: Modeling plant species distributions under future climates: how fine scale do climate projections need to be? *Global Change Biology*, **19**(2), 473-483.
- Franks, S.J. and A.A. Hoffmann, 2012: Genetics of climate change adaptation. *Annual Review of Genetics*, **46**, 185-208.
- Franks, S.J. and A.E. Weis, 2008: A change in climate causes rapid evolution of multiple life-history traits and their interactions in an annual plant. *Journal of Evolutionary Biology*, **21**(5), 1321-1334.
- Freligh, L.E., R.O. Peterson, M. Dovciak, P.B. Reich, J.A. Vucetich, and N. Eisenhauer, 2012: Trophic cascades, invasive species and body-size hierarchies interactively modulate climate change responses of ecotonal temperate-boreal forest. *Philosophical Transactions of the Royal Society B*, **367**(1605), 2955-2961.
- Friend, A., W. Lucht, T.T. Rademacher, R.M. Keribin, R. Betts, P. Cadule, P. Ciais, D.B. Clark, R. Dankers, P. Falloon, A. Ito, R. Kahana, A. Kleidon, M.R. Lomas, K. Nishina, S. Ostberg, R. Pavlick, P. Peylin, S. Schaphoff, N. Vuichard, L. Warszawski, A. Wiltshire, and F.I. Woodward, 2013: Carbon residence time dominates uncertainty in terrestrial vegetation responses to future climate and atmospheric CO₂. *Proceedings of the National Academy of Science of the United States of America* (in press), doi:10.1073/pnas.1222477110.
- Frolking, S., J. Talbot, M.C. Jones, C.C. Treat, J.B. Kauffman, E.S. Tuittila, and N. Roulet, 2011: Peatlands in the Earth's 21st century climate system. *Environmental Reviews*, **19**, 371-396.
- Fujino, J., R. Nair, M. Kainuma, T. Masui, and Y. Matsuoka, 2006: Multi-gas mitigation analysis on stabilization scenarios using AIM global model. *The Energy Journal*, **SI 3**, 343-354.
- Gagen, M., W. Finsinger, F. Wagner-Cremer, D. McCarroll, N.J. Loader, I. Robertson, R. Jalkanen, G. Young, and A. Kirchhefer, 2011: Evidence of changing intrinsic water-use efficiency under rising atmospheric CO₂ concentrations in Boreal Fennoscandia from subfossil leaves and tree ring ¹³C ratios. *Global Change Biology*, **17**(2), 1064-1072.
- Galiano, L., J. Martínez-Vilalta, and F. Lloret, 2010: Drought-induced multifactor decline of Scots pine in the Pyrenees and potential vegetation change by the expansion of co-occurring oak species. *Ecosystems*, **13**(7), 978-991.

- Gallant, D., B.G. Slough, D.G. Reid, and D. Berteaux, 2012: Arctic fox versus red fox in the warming Arctic: four decades of den surveys in north Yukon. *Polar Biology*, **35**(9), 1421-1431.
- Galloway, J.N., A.R. Townsend, J.W. Erisman, M. Bekunda, Z.C. Cai, J.R. Freney, L.A. Martinelli, S.P. Seitzinger, and M.A. Sutton, 2008: Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science*, **320**(5878), 889-892.
- Ganey, J.L. and S.C. Vojta, 2011: Tree mortality in drought-stressed mixed-conifer and ponderosa pine forests, Arizona, USA. *Forest Ecology and Management*, **261**(1), 162-168.
- Gao, J. and Y. Liu, 2011: Climate warming and land use change in Heilongjiang Province, Northeast China. *Applied Geography*, **31**(2), 476-482.
- Gao, X.J. and F. Giorgi, 2008: Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. *Global and Planetary Change*, **62**(3-4), 195-209.
- Garreta, V., P.A. Miller, J. Guiot, C. Hely, S. Brewer, M.T. Sykes, and T. Litt, 2010: A method for climate and vegetation reconstruction through the inversion of a dynamic vegetation model. *Climate Dynamics*, **35**(2-3), 371-389.
- Garrity, S.R., C.D. Allen, S.P. Brumby, C. Gangogadagamage, N.G. McDowell, and D.M. Cai, 2013: Quantifying tree mortality in a mixed species woodland using multitemporal high spatial resolution satellite imagery. *Remote Sensing of Environment*, **129**, 54-65.
- Gaudnik, C., E. Corcket, B. Clement, C.E.L. Delmas, S. Gombert-Courvoisier, S. Muller, C.J. Stevens, and D. Alard, 2011: Detecting the footprint of changing atmospheric nitrogen deposition loads on acid grasslands in the context of climate change. *Global Change Biology*, **17**(11), 3351-3365.
- Gauthier, G., J. Bety, M.-C. Cadieux, P. Legagneux, M. Doiron, C. Chevallier, S. Lai, A. Tarroux, and D. Berteaux, 2013: Long-term monitoring at multiple trophic levels suggests heterogeneity in responses to climate change in the Canadian Arctic tundra. *Philosophical Transactions of the Royal Society B*, **368**(1624), doi:10.1098/rstb.2012.0482.
- Gedalof, F. and A.A. Berg, 2010: Tree ring evidence for limited direct CO₂ fertilization of forests over the 20th century. *Global Biogeochemical Cycles*, **24**(3), GB3027, doi:10.1029/2009GB003699.
- Gerten, D., S. Rost, W. von Bloh, and W. Lucht, 2008: Causes of change in 20th century global river discharge. *Geophysical Research Letters*, **35**(20), L20405, doi:10.1029/2008GL035258.
- Ghermandi, L., M.I.D. Curth, J. Franzese, and S. Gonzalez, 2010: Non-linear ecological processes, fires, environmental heterogeneity and shrub invasion in northwestern Patagonia. *Ecological Modelling*, **221**(1), 113-121.
- Giannakopoulos, C., P. Le Sager, M. Bindi, M. Moriondo, E. Kostopoulou, and C.M. Goodess, 2009: Climatic changes and associated impacts in the Mediterranean resulting from a 2 degrees C global warming. *Global and Planetary Change*, **68**(3), 209-224.
- Gibson, D.J. and L.C. Hulbert, 1987: Effects of fire, topography and year-to-year climatic variation on species composition in tallgrass prairie. *Vegetatio*, **72**(3), 175-185.
- Gibson, L., T.M. Lee, L.P. Koh, B.W. Brook, T.A. Gardner, J. Barlow, C.A. Peres, C.J.A. Bradshaw, W.F. Laurance, T.E. Lovejoy, and N.S. Sodhi, 2011: Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature*, **478**(7369), 378-381.
- Gienapp, P., C. Teplitsky, J.S. Alho, J.A. Mills, and J. Merila, 2008: Climate change and evolution: disentangling environmental and genetic responses. *Molecular Ecology*, **17**(1), 167-178.
- Gienapp, P., M. Lof, T.E. Reed, J. McNamara, S. Verhulst, and M.E. Visser, 2013: Predicting demographically sustainable rates of adaptation: can great tit breeding time keep pace with climate change? *Philosophical Transactions of the Royal Society B*, **368**(1610), 20120289, doi:10.1098/rstb.2012.0289.
- Giglio, L., J.T. Randerson, and G.R. van der Werf, 2013: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *Journal of Geophysical Research: Biogeosciences*, **118**(1), 317-328.
- Gilg, O., K.M. Kovacs, J. Aars, J. Fort, G. Gauthier, D. Gremillet, R.A. Ims, H. Meltofte, J. Moreau, E. Post, N.M. Schmidt, G. Yannic, and L. Bollache, 2012: Climate change and the ecology and evolution of Arctic vertebrates. In: *The Year in Ecology and Conservation Biology 2012* [Ostfeld, R.S. and W.H. Schlesinger (eds.)]. Vol. 102 of the Annals of the New York Academy of Sciences, Wiley-Blackwell Publishing (for the New York Academy of Science), Boston, MA, USA, pp. 166-190.
- Gill, A.M., J.Z. Wionarski, and A. York, 1999: *Australians Biodiversity Responses to Fire: Plants, Birds and Invertebrates*. Commonwealth Department of the Environment and Heritage, Canberra, Australia, 267 pp.
- Gill, J.L., J.W. Williams, S.T. Jackson, K.B. Lininger, and G.S. Robinson, 2009: Pleistocene megafaunal collapse, novel plant communities, and enhanced fire regimes in North America. *Science*, **326**(5956), 1100-1103.
- Gillingham, P.K., B. Huntley, W.E. Kunin, and C.D. Thomas, 2012: The effect of spatial resolution on projected responses to climate warming. *Diversity and Distributions*, **18**(10), 990-1000.
- Gilman, S.E., M.C. Urban, J. Tewksbury, G.W. Gilchrist, and R.D. Holt, 2010: A framework for community interactions under climate change. *Trends in Ecology & Evolution*, **25**(6), 325-331.
- Giorgi, F. and P. Lionello, 2008: Climate change projections for the Mediterranean region. *Global and Planetary Change*, **63**(2-3), 90-104.
- Girardin, M.P. and M. Mudelsee, 2008: Past and future changes in Canadian boreal wildfire activity. *Ecological Applications*, **18**(2), 391-406.
- Girardin, M.P., A.A. Ali, C. Carcaillet, M. Mudelsee, I. Drobyshev, C. Hely, and Y. Bergeron, 2009: Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s. *Global Change Biology*, **15**(11), 2751-2769.
- Girardin, M.P., P.Y. Bernier, and S. Gauthier, 2011: Increasing potential NEP of eastern boreal North American forests constrained by decreasing wildfire activity. *Ecosphere*, **2**, 25, doi:10.1890/ES10-00159.1.
- Girardin, M.P., X.J. Guo, P.Y. Bernier, F. Raulier, and S. Gauthier, 2012: Changes in growth of pristine boreal North American forests from 1950 to 2005 driven by landscape demographics and species traits. *Biogeosciences*, **9**(7), 2523-2536.
- Girardin, M.P., A.A. Ali, C. Carcaillet, S. Gauthier, C. Hely, H. Le Goff, A. Terrier, and Y. Bergeron, 2013a: Fire in managed forests of eastern Canada: risks and options. *Forest Ecology and Management*, **294**, 238-249.
- Girardin, M.P., A.A. Ali, C. Carcaillet, O. Blarquez, C. Hely, A. Terrier, A. Genries, and Y. Bergeron, 2013b: Vegetation limits the impact of a warm climate on boreal wildfires. *New Phytologist*, **199**(4), 1001-1011.
- Goetz, S.J., M.C. Mack, K.R. Gurney, J.T. Randerson, and R.A. Houghton, 2007: Ecosystem responses to recent climate change and fire disturbance at northern high latitudes: observations and model results contrasting northern Eurasia and North America. *Environmental Research Letters*, **2**(4), 045031, doi:10.1088/1748-9326/2/4/045031.
- Goetz, S.J., H.E. Epstein, U. Bhatt, G.J. Jia, J.O. Kaplan, H. Lischke, Q. Yu, A. Bunn, A. Lloyd, D. Alcaraz, P.S.A. Beck, J. Comiso, M.K. Reynolds, and D.A. Walker, 2011: Recent changes in Arctic vegetation: satellite observations and simulation model predictions. In: *Eurasian Arctic Land Cover and Land Use in a Changing Climate* [Gutman, G. and A. Reissell (eds.)]. Springer-Verlag, Amsterdam, Netherlands, pp. 9-36.
- Goldblum, D. and L.S. Rigg, 2010: The deciduous forest – boreal forest ecotone. *Geography Compass*, **4**(7), 701-717.
- Golding, N. and R. Betts, 2008: Fire risk in Amazonia due to climate change in the HadCM3 climate model: potential interactions with deforestation. *Global Biogeochemical Cycles*, **22**(4), GB4007, doi:10.1029/2007GB003166.
- Gonzalez, P., 2001: Desertification and a shift of forest species in the West African Sahel. *Climate Research*, **17**(2), 217-228.
- Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek, 2010: Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. *Global Ecology and Biogeography*, **19**(6), 755-768.
- Gonzalez, P., C.J. Tucker, and H. Sy, 2012: Tree density and species decline in the African Sahel attributable to climate. *Journal of Arid Environments*, **78**(0), 55-64.
- Good, P., C. Jones, J. Lowe, R. Betts, B. Booth, and C. Huntingford, 2011a: Quantifying environmental drivers of future tropical forest extent. *Journal of Climate*, **24**(5), 1337-1349.
- Good, P., J. Caesar, D. Bernie, J.A. Lowe, P. van der Linden, S.N. Gosling, R. Warren, N.W. Arnell, S. Smith, J. Bamber, T. Payne, S. Laxon, M. Srokosz, S. Stith, N. Gedney, G. Harris, H. Hewitt, L. Jackson, C.D. Jones, F. O'Connor, J. Ridley, M. Vellinga, P. Halloran, and D. McNeall, 2011b: A review of recent developments in climate change science. Part I: understanding of future change in the large-scale climate system. *Progress in Physical Geography*, **35**(3), 281-296.
- Good, P., C. Jones, J. Lowe, R. Betts, and N. Gedney, 2013: Comparing tropical forest projections from two generations of Hadley Centre Earth System Models, HadGEM2-ES and HadCM3LC. *Journal of Climate*, **26**(2), 495-511.
- Gordo, O., 2007: Why are bird migration dates shifting? A review of weather and climate effects on avian migratory phenology. *Climate Research*, **35**(1-2), 37-58.
- Gordo, O. and J.J. Sanz, 2005: Phenology and climate change: a long-term study in a Mediterranean locality. *Oecologia*, **146**(3), 484-495.
- Gordo, O. and J.J. Sanz, 2010: Impact of climate change on plant phenology in Mediterranean ecosystems. *Global Change Biology*, **16**(3), 1082-1106.

- Gottfried, M., H. Pauli, A. Futschik, M. Akhalkatsi, P. Barancok, J.L.B. Alonso, G. Coldea, J. Dick, B. Erschbamer, M.R.F. Calzado, G. Kazakis, J. Krajci, P. Larsson, M. Mallaun, O. Michelsen, D. Moiseev, P. Moiseev, U. Molau, A. Merzouki, L. Nagy, G. Nakhutsrishvili, B. Pedersen, G. Pelino, M. Puscas, G. Rossi, A. Stanisci, J.P. Theurillat, M. Tomaselli, L. Villar, P. Vittoz, I. Vogiatzakis, and G. Grabherr, 2012:** Continent-wide response of mountain vegetation to climate change. *Nature Climate Change*, **2(2)**, 111-115.
- Graiprab, P., K. Pongput, N. Tangtham, and P.W. Gassman, 2010:** Hydrologic evaluation and effect of climate change on the At Samat watershed, Northeastern Region, Thailand. *International Agricultural Engineering Journal*, **19(2)**, 12-22.
- Green, R.E., Y.C. Collingham, S.G. Willis, R.D. Gregory, K.W. Smith, and B. Huntley, 2008:** Performance of climate envelope models in retrodicting recent changes in bird population size from observed climatic change. *Biology Letters*, **4(5)**, 599-602.
- Griesbauer, H.P. and D.S. Green, 2012:** Geographic and temporal patterns in white spruce climate – growth relationships in Yukon, Canada. *Forest Ecology and Management*, **267**, 215-227.
- Grime, J.P., J.D. Fridley, A.P. Askew, K. Thompson, J.G. Hodgson, and C.R. Bennet, 2008:** Long-term resistance to simulated climate change in an infertile grassland. *Proceedings of the National Academy of Sciences of the United States of America*, **105(29)**, 10028-10032.
- Groisman, P.Y., R.W. Knight, and T.R. Karl, 2012:** Changes in intense precipitation over the central United States. *Journal of Hydrometeorology*, **13(1)**, 47-66.
- Grosse, G., J. Harden, M. Turetsky, A.D. McGuire, P. Camill, C. Tarnocai, S. Frolking, E.A.G. Schuur, T. Jorgenson, S. Marchenko, V. Romanovsky, K.P. Wickland, N. French, M. Waldrop, L. Bourgeau-Chavez, and R.G. Striegl, 2011:** Vulnerability of high-latitude soil organic carbon in North America to disturbance. *Journal of Geophysical Research: Biogeosciences*, **116(G4)**, G00K06, doi:10.1029/2010JG001507.
- Gruber, N. and J.N. Galloway, 2008:** An Earth-system perspective of the global nitrogen cycle. *Nature*, **451(7176)**, 293-296.
- Guglielmin, M. and N. Cannone, 2012:** A permafrost warming in a cooling Antarctica? *Climatic Change*, **111(2)**, 177-195.
- Gunderson, A.R. and M. Leal, 2012:** Geographic variation in vulnerability to climate warming in a tropical Caribbean lizard. *Functional Ecology*, **26(4)**, 783-793.
- Gunderson, C.A., N.T. Edwards, A.V. Walker, K.H. O'Hara, C.M. Campion, and P.J. Hanson, 2012:** Forest phenology and a warmer climate – growing season extension in relation to climatic provenance. *Global Change Biology*, **18(6)**, 2008-2025.
- Gunderson, L. and C.S. Holling (eds.), 2001:** *Panarchy: Understanding Transformations in Systems of Humans and Nature*. Island Press, Washington, DC, USA, 507 pp.
- Gyllström, M., L.A. Hansson, E. Jeppesen, F. Garcia-Criado, E. Gross, K. Irvine, T. Kairesalo, R. Kornijow, M.R. Miracle, M. Nykanen, T. Noges, S. Romo, D. Stephen, E. Van Donk, and B. Moss, 2005:** The role of climate in shaping zooplankton communities of shallow lakes. *Limnology and Oceanography*, **50(6)**, 2008-2021.
- Haberl, H., K.H. Erb, F. Krausmann, A. Bondeau, C. Lauk, C. Müller, C. Plutzer, and J.K. Steinberger, 2011:** Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and Bioenergy*, **35(12)**, 4753-4769.
- Hague, M.J., M.R. Ferrari, J.R. Miller, D.A. Patterson, G.L. Russell, A.P. Farrell, and S.G. Hinch, 2011:** Modelling the future hydroclimatology of the lower Fraser River and its impacts on the spawning migration survival of sockeye salmon. *Global Change Biology*, **17(1)**, 87-98.
- Haider, S., C. Kueffer, P.J. Edwards, and J.M. Alexander, 2012:** Genetically based differentiation in growth of multiple non-native plant species along a steep environmental gradient. *Oecologia*, **170(1)**, 89-99.
- Hall, J.S., M.S. Ashton, E.J. Garen, and S. Jose, 2011:** The ecology and ecosystem services of native trees: implications for reforestation and land restoration in Mesoamerica. *Forest Ecology and Management*, **261(10)**, 1553-1557.
- Halley, J.M., Y. Iwasa, and D. Vokou, 2013:** Comment on "Extinction debt and windows of conservation opportunity in the Brazilian Amazon". *Science*, **339(6117)**, 271.
- Hamilton, S.K., 2010:** Biogeochemical implications of climate change for tropical rivers and floodplains. *Hydrobiologia*, **657(1)**, 19-35.
- Hampe, A., 2011:** Plants on the move: the role of seed dispersal and initial population establishment for climate-driven range expansions. *Acta Oecologica: International Journal of Ecology*, **37(6)**, 666-673.
- Hannah, L., 2012:** *Saving a Million Species: Extinction Risk from Climate Change*. Island Press, Washington, DC, USA, 419 pp.
- Hannah, L., G. Midgley, S. Andelman, M. Araujo, G. Hughes, E. Martinez-Meyer, R. Pearson, and P. Williams, 2007:** Protected area needs in a changing climate. *Frontiers in Ecology and the Environment*, **5(3)**, 131-138.
- Hansen, M.M., I. Olivieri, D.M. Waller, E.E. Nielsen, and The GeM Working Group, 2012:** Monitoring adaptive genetic responses to environmental change. *Molecular Ecology*, **21(6)**, 1311-1329.
- Hari, P. and L. Kulmata, 2008:** *Boreal Forest and Climate Change*. Springer, New York, NY, USA, 582 pp.
- Harris, J.A., R.J. Hobbs, E. Higgs, and J. Aronson, 2006:** Ecological restoration and global climate change. *Restoration Ecology*, **14**, 170-176.
- Harrison, S.P. and M.F.S. Goni, 2010:** Global patterns of vegetation response to millennial-scale variability and rapid climate change during the last glacial period. *Quaternary Science Reviews*, **29(21-22)**, 2957-2980.
- Harsch, M.A., P.E. Hulme, M.S. McGlone, and R.P. Duncan, 2009:** Are treelines advancing? A global meta-analysis of treeline response to climate warming. *Ecology Letters*, **12(10)**, 1040-1049.
- Hastings, A., 2004:** Transients: the key to long-term ecological understanding? *Trends in Ecology & Evolution*, **19(1)**, 39-45.
- Haxeltine, A. and I.C. Prentice, 1996:** BIOME3: an equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. *Global Biogeochemical Cycles*, **10**, 693-709.
- Hayes, F., M.L.M. Jones, G. Mills, and M. Ashmore, 2007:** Meta-analysis of the relative sensitivity of semi-natural vegetation species to ozone. *Environmental Pollution*, **146(3)**, 754-762.
- Hayes, K.R. and S.C. Barry, 2008:** Are there any consistent predictors of invasion success? *Biological Invasions*, **10(4)**, 483-506.
- Haywood, A.M. and P.J. Valdes, 2006:** Vegetation cover in a warmer world simulated using a dynamic global vegetation model for the Mid-Pliocene. *Palaeogeography Palaeoclimatology Palaeoecology*, **237(2-4)**, 412-427.
- Haywood, A.M., A. Ridgwell, D.J. Lunt, D.J. Hill, M.J. Pound, H.J. Dowsett, A.M. Dolan, J.E. Francis, and M. Williams, 2011:** Are there pre-Quaternary geological analogues for a future greenhouse warming? *Philosophical Transactions of the Royal Society A*, **369(1938)**, 933-956.
- Heckenberger, M.J., J.C. Russell, J.R. Toney, and M.J. Schmidt, 2007:** The legacy of cultural landscapes in the Brazilian Amazon: implications for biodiversity. *Philosophical Transactions of the Royal Society B*, **362(1478)**, 197-208.
- Hegarty, M.J., 2012:** Invasion of the hybrids. *Molecular Ecology*, **21(19)**, 4669-4671.
- Hegglin, M.I. and T.G. Shepherd, 2009:** Large climate-induced changes in ultraviolet index and stratosphere-to-troposphere ozone flux. *Nature Geoscience*, **10(10)**, 687-691.
- Hegland, S.J., A. Nielsen, A. Lazaro, A.L. Bjerknes, and Totland, 2009:** How does climate warming affect plant-pollinator interactions? *Ecology Letters*, **12(2)**, 184-195.
- Hejman, M., P. Hejmanova, V. Pavlu, and J. Benes, 2013:** Origin and history of grasslands in Central Europe – a review. *Grass and Forage Science*, **68(3)**, 345-363.
- Hellden, U. and C. Tottrup, 2008:** Regional desertification: a global synthesis. *Global and Planetary Change*, **64(3-4)**, 169-176.
- Heller, N.E. and E.S. Zavaleta, 2009:** Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological Conservation*, **142(1)**, 14-32.
- Hellmann, J.J., J.E. Byers, B.G. Bierwagen, and J.S. Dukes, 2008:** Five potential consequences of climate change for invasive species. *Conservation Biology*, **22(3)**, 534-543.
- Hemery, G.E., 2008:** Forest management and silvicultural responses to projected climate change impacts on European broadleaved trees and forests. *International Forestry Review*, **10(4)**, 591-607.
- Hendry, A.P. and A. Gonzalez, 2008:** Whither adaptation? *Biology & Philosophy*, **23(5)**, 673-699.
- Hermoso, V. and M. Clavero, 2011:** Threatening processes and conservation management of endemic freshwater fish in the Mediterranean basin: a review. *Marine and Freshwater Research*, **62(3)**, 244-254.
- Hewitt, N., N. Klenk, A.L. Smith, D.R. Bazely, N. Yan, S. Wood, J.I. MacLellan, C. Lipsig-Mummé, and I. Henriques, 2011:** Taking stock of the assisted migration debate. *Biological Conservation*, **144(11)**, 2560-2572.
- Hickler, T., B. Smith, I.C. Prentice, K. Mjöfors, P. Miller, A. Arneth, and M.T. Sykes, 2008:** CO₂ fertilization in temperate FACE experiments not representative of boreal and tropical forests. *Global Change Biology*, **14**, 1531-1542.
- Hickler, T., K. Vohland, J. Feehan, P.A. Miller, B. Smith, L. Costa, T. Giesecke, S. Fronzek, T.R. Carter, W. Cramer, I. Kühn, and M.T. Sykes, 2012:** Projecting the future distribution of European potential natural vegetation zones with a generalized, tree species-based dynamic vegetation model. *Global Ecology and Biogeography*, **21(1)**, 50-63.

- Hickling, R., D.B. Roy, J.K. Hill, R. Fox, and C.D. Thomas, 2006: The distributions of a wide range of taxonomic groups are expanding polewards. *Global Change Biology*, **12**(3), 450-455.
- Higgins, S.I. and S. Scheiter, 2012: Atmospheric CO₂ forces abrupt vegetation shifts locally, but not globally. *Nature*, **488**(7410), 209-212.
- Higgins, S.I., J.S. Clark, R. Nathan, T. Hovestadt, F. Schurr, J.M.V. Fragoso, M.R. Aguiar, E. Ribbens, and S. Lavorel, 2003: Forecasting plant migration rates: managing uncertainty for risk assessment. *Journal of Ecology*, **91**(3), 341-347.
- Higgins, S.I., R.B. O'Hara, and C. Romermann, 2012: A niche for biology in species distribution models. *Journal of Biogeography*, **39**(12), 2091-2095.
- Higuera, P.E., M.L. Chipman, J.L. Barnes, M.A. Urban, and F.S. Hu, 2011: Variability of tundra fire regimes in Arctic Alaska: millennial-scale patterns and ecological implications. *Ecological Applications*, **21**(8), 3211-3226.
- Hijjoka, Y., Y. Matsuoka, H. Nishimoto, and M. Kainuma, (2008): Global GHG emission scenarios under GHG concentration stabilization targets. *Journal of Global Environmental Engineering*, **13**, 97-108.
- Hill, P.W., J. Farrar, P. Roberts, M. Farrell, H. Grant, K.K. Newsham, D.W. Hopkins, R.D. Bardgett, and D.L. Jones, 2011: Vascular plant success in a warming Antarctic may be due to efficient nitrogen acquisition. *Nature Climate Change*, **1**(1), 50-53.
- Hinzman, L.D., N.D. Bettez, W.R. Bolton, F.S. Chapin III, M.B. Dyrgerov, C.L. Fastie, B. Griffith, R.D. Hollister, A. Hope, H.P. Huntington, A.M. Jensen, G.J. Jia, T. Jorgenson, D.L. Kane, D.R. Klein, G. Kofinas, A.H. Lynch, A.H. Lloyd, A.D. McGuire, F.E. Nelson, W.C. Oechel, T.E. Osterkamp, C.H. Racine, V.E. Romanovsky, R.S. Stone, D.A. Stow, M. Sturm, C.E. Tweedie, G.L. Vourlitis, M.D. Walker, D.A. Walker, P.J. Webber, J.M. Welker, K. Winker, and K. Yoshikawa, 2005: Evidence and implications of recent climate change in northern Alaska and other arctic regions. *Climatic Change*, **72**(3), 251-298.
- Hockey, P.A.R., C. Sirami, A.R. Ridley, G.F. Midgley, and H.A. Babiker, 2011: Interrogating recent range changes in South African birds: confounding signals from land use and climate change present a challenge for attribution. *Diversity and Distributions*, **17**(2), 254-261.
- Hodgson, J.A., C.D. Thomas, C. Dytham, J.M.J. Travis, and S.J. Cornell, 2012: The speed of range shifts in fragmented landscapes. *PLoS One*, **7**(10), e47141, doi:10.1371/journal.pone.0047141.
- Hoegh-Guldberg, O., L. Hughes, S. McIntyre, D.B. Lindenmayer, C. Parmesan, H.P. Possingham, and C.D. Thomas, 2008: Assisted colonization and rapid climate change. *Science*, **321**(5887), 345-346.
- Hof, C., M.B. Araujo, W. Jetz, and C. Rahbek, 2011a: Additive threats from pathogens, climate and land-use change for global amphibian diversity. *Nature*, **480**(7378), 516-519.
- Hof, C., I. Levinsky, M.B. Araujo, and C. Rahbek, 2011b: Rethinking species' ability to cope with rapid climate change. *Global Change Biology*, **17**(9), 2987-2990.
- Hoffmann, A.A. and C.M. Sgro, 2011: Climate change and evolutionary adaptation. *Nature*, **470**(7335), 479-485.
- Hoffmann, M., C. Hilton-Taylor, A. Angulo, M. Bohm, T.M. Brooks, S.H.M. Butchart, K.E. Carpenter, J. Chanson, B. Collen, N.A. Cox, W.R.T. Darwall, N.K. Dulvy, L.R. Harrison, V. Katariya, C.M. Pollock, S. Quader, N.I. Richman, A.S.L. Rodrigues, M.F. Tognelli, J.C. Vie, J.M. Aguiar, D.J. Allen, G.R. Allen, G. Amori, N.B. Ananjeva, F. Andreone, P. Andrew, A.L.A. Ortiz, J.E.M. Baillie, R. Baldi, B.D. Bell, S.D. Biju, J.P. Bird, P. Black-Decima, J.J. Blanc, F. Bolanos, W. Bolivar, I.J. Burfield, J.A. Burton, D.R. Capper, F. Castro, G. Catullo, R.D. Cavanagh, A. Channing, N.L. Chao, A.M. Chenery, F. Chiozza, V. Clausnitzer, N.J. Collar, L.C. Collett, B.B. Collette, C.F.C. Fernandez, M.T. Craig, M.J. Crosby, N. Cumberlidge, A. Cuttelod, A.E. Derocher, A.C. Diesmos, J.S. Donaldson, J.W. Duckworth, G. Dutton, S.K. Dutta, R.H. Emslie, A. Farjon, S. Fowler, J. Freyhof, D.L. Garshelis, J. Gerlach, D.J. Gower, T.D. Grant, G.A. Hammerson, R.B. Harris, L.R. Heaney, S.B. Hedges, J.M. Hero, B. Hughes, S.A. Hussain, J. Icochea, R.F. Inger, N. Ishii, D.T. Iskandar, R.K.B. Jenkins, Y. Kaneko, M. Kottelat, K.M. Kovacs, S.L. Kuzmin, E. La Marca, J.F. Lamoreux, M.W.N. Lau, E.O. Lavilla, K. Leus, R.L. Lewison, G. Lichtenstein, S.R. Livingstone, V. Lukoschek, D.P. Mallon, P.J.K. McGowan, A. McIvor, P.D. Moehlman, S. Molur, A.M. Alonso, J.A. Musick, K. Nowell, R.A. Nussbaum, W. Olech, N.L. Orlov, T.J. Papenfuss, G. Parra-Olea, W.F. Perrin, B.A. Polidoro, M. Pourkazemi, P.A. Racey, J.S. Ragle, M. Ram, G. Rathbun, R.P. Reynolds, A.G.J. Rhodin, S.J. Richards, L.O. Rodriguez, S.R. Ron, C. Rondinini, A.B. Rylands, Y.S. de Mitcheson, J.C. Sanciangco, K.L. Sanders, G. Santos-Barrera, J. Schipper, C. Self-Sullivan, Y.C. Shi, A. Shoemaker, F.T. Short, C. Sillero-Zubiri, D.L. Silvano, K.G. Smith, A.T. Smith, J. Snoeks, A.J. Statteford, A. Ailleres, A.B. Taber, B.K. Talukdar, H.J. Temple, R. Timmins, J.A. Tobiasias, K. Tsytsulina, D. Tweddle, C. Ubeda, S.V. Valenti, P.P. van Dijk, L.M. Veiga, A. Veloso, D.C. Wege, M. Wilkinson, E.A. Williamson, F. Xie, B.E. Young, H.R. Akcakaya, L. Bennun, T.M. Blackburn, L. Boitani, H.T. Dublin, G.A.B. da Fonseca, C. Gascon, T.E. Lacher, G.M. Mace, S.A. Mainka, J.A. McNeely, R.A. Mittermeier, G.M. Reid, J.P. Rodriguez, A.A. Rosenberg, M.J. Samways, J. Smart, B.A. Stein, and S.N. Stuart, 2010: The impact of conservation on the status of the World's vertebrates. *Science*, **330**(6010), 1503-1509.
- Hofmann, G.E. and A.E. Todgham, 2010: Living in the now: physiological mechanisms to tolerate a rapidly changing environment. *Annual Review of Physiology*, **72**, 127-145.
- Hofmockel, K.S., D.R. Zak, K.K. Moran, and J.D. Jastrow, 2011: Changes in forest soil organic matter pools after a decade of elevated CO₂ and O₃. *Soil Biology and Biochemistry*, **43**(7), 1518-1527.
- Hogg, E.H., J.P. Brandt, and M. Michaelian, 2008: Impact of a regional drought on the productivity, dieback and biomass of western Canadian aspen forests. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **38**, 1373-1384.
- Hole, D.G., S.G. Willis, D.J. Pain, L.D. Fishpool, S.H.M. Butchart, Y.C. Collingham, C. Rahbek, and B. Huntley, 2009: Projected impacts of climate change on a continent-wide protected area network. *Ecology Letters*, **12**(5), 420-431.
- Hole, D.G., B. Huntley, J. Arinaitwe, S.H.M. Butchart, Y.C. Collingham, L.D.C. Fishpool, D.J. Pain, and S.G. Willis, 2011: Toward a management framework for networks of protected areas in the face of climate change. *Conservation Biology*, **25**(2), 305-315.
- Holmgren, M., P. Stapp, C.R. Dickman, C. Gracia, S. Graham, J.R. Gutiérrez, C. Hice, F. Jaksic, D.A. Kelt, M. Letnic, M. Lima, B.C. López, P.L. Meserve, W.B. Milstead, G.A. Polis, M.A. Previtali, M. Richter, S. Sabaté, and F.A. Squeo, 2006: Extreme climatic events shape arid and semiarid ecosystems. *Frontiers in Ecology and the Environment*, **4**(2), 87-95.
- Hongve, D., G. Riise, and J.F. Kristiansen, 2004: Increased colour and organic acid concentrations in Norwegian forest lakes and drinking water – a result of increased precipitation? *Aquatic Sciences*, **66**(2), 231-238.
- Hooijer, A., S. Page, J.G. Canadell, M. Silvius, J. Kwadijk, H. Wosten, and J. Jauhainen, 2010: Current and future CO₂ emissions from drained peatlands in Southeast Asia. *Biogeosciences*, **7**(5), 1505-1514.
- Hoover, S.E.R., J.J. Ladley, A.A. Shchepetkina, M. Tisch, S.P. Gieseg, and J.M. Tylianakis, 2012: Warming, CO₂, and nitrogen deposition interactively affect a plant-pollinator mutualism. *Ecology Letters*, **15**(3), 227-234.
- Horowitz, L.W., 2006: Past present and future concentrations of tropospheric ozone and aerosols: methodology, ozone evaluation, and sensitivity to aerosol wet removal. *Journal of Geophysical Research: Atmospheres*, **111**(D22), D22211, doi:10.1029/2005JD006937.
- Hosonuma, N., M. Herold, V. De Sy, R.S. De Fries, M. Brockhaus, L. Verchot, A. Angelsen, and E. Romijn, 2012: An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*, **7**(4), 044009, doi:10.1088/1748-9326/7/4/044009.
- Høye, T.T., E. Post, H. Meltofte, N.M. Schmidt, and M.C. Forchhammer, 2007: Rapid advancement of spring in the High Arctic. *Current Biology*, **17**(12), R449-R451.
- Hoyle, C.R., M. Boy, N.M. Donahue, J.L. Fry, M. Glasius, A. Guenther, A.G. Hallar, K.H. Hartz, M.D. Petters, T. Petaja, T. Rosenoern, and A.P. Sullivan, 2011: A review of the anthropogenic influence on biogenic secondary organic aerosol. *Atmospheric Chemistry and Physics*, **11**(1), 321-343.
- Huang, D., R.A. Haack, and R. Zhang, 2011: Does global warming increase establishment rates of invasive alien species? A Centennial time series analysis. *PLoS One*, **6**(9), doi:10.1371/journal.pone.0024733.
- Huang, J.G., Y. Bergeron, B. Dennerle, F. Berninger, and J. Tardif, 2007: Response of forest trees to increased atmospheric CO₂. *Critical Reviews in Plant Sciences*, **26**(5-6), 265-283.
- Huey, R.B., M.R. Kearney, A. Krockenberger, J.A.M. Holtum, M. Jess, and S.E. Williams, 2012: Predicting organismal vulnerability to climate warming: roles of behaviour, physiology and adaptation. *Philosophical Transactions of the Royal Society B*, **367**(1596), 1665-1679.
- Hughes, R.F., S.R. Archer, G.P. Asner, C.A. Wessman, C.H.A.D. McMurry, J.I.M. Nelson, and R.J. Ansley, 2006: Changes in aboveground primary production and carbon and nitrogen pools accompanying woody plant encroachment in a temperate savanna. *Global Change Biology*, **12**(9), 1733-1747.
- Hughes, T.P., C. Linares, V. Dakos, I.A. van de Leemput, and E.H. van Nes, 2013: Living dangerously on borrowed time during slow, unrecognized regime shifts. *Trends in Ecology & Evolution*, **28**(3), 149-155.

- Hülber, K., M. Winkler, and G. Grabherr, 2010: Intra-seasonal climate and habitat-specific variability controls the flowering phenology of high alpine plant species. *Functional Ecology*, **24**(2), 245-252.
- Hunt, A. and P. Watkiss, 2011: Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change*, **104**(1), 13-49.
- Hunter, C.M., H. Caswell, M.C. Runge, E.V. Regehr, S.C. Amstrup, and I. Stirling, 2010: Climate change threatens polar bear populations: a stochastic demographic analysis. *Ecology*, **91**(10), 2883-2897.
- Huntingford, C., P.M. Cox, L.M. Mercado, S. Sitch, N. Bellouin, O. Boucher, and N. Gedney, 2011: Highly contrasting effects of different climate forcing agents on terrestrial ecosystem services. *Philosophical Transactions of the Royal Society A*, **369**(1943), 2026-2037.
- Huntingford, C., P. Zelazowski, D. Galbraith, L.M. Mercado, S. Sitch, R. Fisher, M. Lomas, A. P. Walker, C.D. Jones, B.B.B. Booth, Y. Malhi, D. Hemming, G. Kay, P. Good, S.L. Lewis, O.L. Phillips, O.K. Atkin, J. Lloyd, E. Gloor, J. Zaragoza-Castells, P. Meir, R. Betts, P.P. Harris, C. Nobre, J. Marengo, and P.M. Cox, 2013: Simulated resilience of tropical rainforests to CO₂-induced climate change. *Nature Geoscience*, **6**, 268-273.
- Huntington, T.G., 2008: CO₂-induced suppression of transpiration cannot explain increasing runoff. *Hydrological Processes*, **22**(2), 311-314.
- Hurt, G.C., L.P. Chini, S. Froking, R.A. Betts, J. Feddema, G. Fischer, J.P. Fisk, K. Hibbard, R.A. Houghton, A. Janetos, C.D. Jones, G. Kindermann, T. Kinoshita, K.K. Goldewijk, K. Riahi, E. Shevliakova, S. Smith, E. Stehfest, A. Thomson, P. Thornton, D.P.v. Vuuren, and Y.P. Wang, 2011: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Climatic Change*, **109**, 117-161.
- Husby, A., M.E. Visser, and L.E.B. Kruuk, 2011: Speeding up microevolution: the effects of increasing temperature on selection and genetic variance in a wild bird population. *PLoS Biology*, **9**(2), e1000585, doi:10.1371/journal.pbio.1000585.
- Ihlow, F., J. Dambach, J.O. Engler, M. Flecks, T. Hartmann, S. Nekum, H. Rajaei, and D. Rodder, 2012: On the brink of extinction? How climate change may affect global chelonian species richness and distribution. *Global Change Biology*, **18**(5), 1520-1530.
- Innes, J.L., 1992: Observations on the condition of beech (*Fagus sylvatica* L.) in Britain in 1990. *Forestry*, **65**(1), 35-60.
- Inouye, D.W., 2008: Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. *Ecology*, **89**(2), 353-362.
- INPE, 2013: *Projeto Desmatamento (PRODES): Monitoramento da Floresta Amazonica por Satelite*. Cited 2013, www.obt.inpe.br/prodes/.
- IPCC, 2012: Summary for policymakers. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-21.
- Iverson, L.R., M.W. Schwartz, and A.M. Prasad, 2004: How fast and far might tree species migrate in the eastern United States due to climate change? *Global Ecology and Biogeography*, **13**(3), 209-219.
- Iverson, L.R., A. Prasad, and S. Matthews, 2008: Modeling potential climate change impacts on the trees of the northeastern United States. *Mitigation and Adaptation Strategies for Global Change*, **13**(5-6), 487-516.
- Iverson, L.R., A.M. Prasad, S.N. Matthews, and M.P. Peters, 2011: Lessons learned while integrating habitat, dispersal, disturbance, and life-history traits into species habitat models under climate change. *Ecosystems*, **14**(6), 1005-1020.
- Jackson, R.B., E.G. Jobbagy, R. Avissar, S.B. Roy, D.J. Barrett, C.W. Cook, K.A. Farley, D.C. le Maitre, B.A. McCarl, and B.C. Murray, 2005: Trading water for carbon with biological sequestration. *Science*, **310**(5756), 1944-1947.
- Jackson, S.T. and R.J. Hobbs, 2009: Ecological restoration in the light of ecological history. *Science*, **325**(5940), 567-569.
- Jackson, S.T. and J.T. Overpeck, 2000: Responses of plant populations and communities to environmental changes of the Late Quaternary. *Paleobiology*, **26**(4), 194-220.
- Jackson, S.T., S.T. Gray, and B. Shuman, 2009: Paleoecology and resource management in a dynamic landscape: case studies from the Rocky Mountain headwaters. In: *Conservation Paleobiology: Using the Past to Manage for the Future* [Dietl, G.P. and K.W. Flessa (eds.)]. The Paleontological Society Papers, Vol. 15, Boulder, CO, USA, pp. 61-80.
- Jacobsen, D., A.M. Milner, L.E. Brown, and O. Dangles, 2012: Biodiversity under threat in glacier-fed river systems. *Nature Climate Change*, **2**(5), 361-364.
- Jamieson, M.A., A.M. Trowbridge, K.F. Raffa, and R.L. Lindroth, 2012: Consequences of climate warming and altered precipitation patterns for plant-insect and multitrophic interactions. *Plant Physiology*, **160**(4), 1719-1727.
- Jansen, E., J. Overpeck, K.R. Briffa, J.-C. Duplessy, F. Joos, V. Masson-Delmotte, D. Olago, B. Otto-Bliesner, W.R. Peltier, S. Rahmstorf, R. Ramesh, D. Raynaud, D. Rind, O. Solomina, R. Villalba, and D. Zhang, 2007: Paleoclimate. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 433-497.
- Jaramillo, C., D. Ochoa, L. Contreras, M. Pagani, H. Carvajal-Ortiz, L.M. Pratt, S. Krishnan, A. Cardona, M. Romero, L. Quiroz, G. Rodriguez, M.J. Rueda, F. de la Parra, S. Moron, W. Green, G. Bayona, C. Montes, O. Quintero, R. Ramirez, G. Mora, S. Schouten, H. Bermudez, R. Navarrete, F. Parra, M. Alvaran, J. Osorno, J.L. Crowley, V. Valencia, and J. Vervoort, 2010: Effects of rapid global warming at the Paleocene-Eocene boundary on neotropical vegetation. *Science*, **330**(6006), 957-961.
- Jarvis, P.G., 1976: The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Philosophical Transactions of the Royal Society B*, **273**, 593-610.
- Jenerette, G.D., S.L. Harlan, W.L. Stefanov, and C.A. Martin, 2011: Ecosystem services and urban heat riskscape moderation: water, green spaces, and social inequality in Phoenix, AZ, USA. *Ecological Applications*, **21**(7), 2637-2651.
- Jenkins, K.M. and A.J. Boulton, 2007: Detecting impacts and setting restoration targets in arid-zone rivers: aquatic micro-invertebrate responses to reduced floodplain inundation. *Journal of Applied Ecology*, **44**(4), 823-832.
- Jensen, K.D., C. Beier, A. Michelsen, and B.A. Emmett, 2003: Effects of experimental drought on microbial processes in two temperate heathlands at contrasting water conditions. *Applied Soil Ecology*, **24**(2), 165-176.
- Jeong, S.J., C.H. Ho, H.J. Gim, and M.E. Brown, 2011: Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982-2008. *Global Change Biology*, **17**(7), 2385-2399.
- Jia, B., Y. Ma, and K. Qiu, 2009: Dynamics of the vegetation coverage in recent 15 years in Yijinhuluo County, Inner Mongolia, China. *Arid Land Geography*, **32**(4), 481-487.
- Jia, G.J., H.E. Epstein, and D.A. Walker, 2009: Vegetation greening in the Canadian Arctic related to decadal warming. *Journal of Environmental Monitoring*, **11**(12), 2231-2238.
- Jin, J., S. Lu, S. Li, and N.L. Miller, 2010: Impact of land use change on the local climate over the Tibetan Plateau. *Advances in Meteorology*, **2010**, 837480, doi:10.1155/2010/837480.
- Jin, Y., J.T. Randerson, S.J. Goetz, P.S.A. Beck, M.M. Loranty, and M.L. Goulden, 2012: The influence of burn severity on postfire vegetation recovery and albedo change during early succession in North American boreal forests. *Journal of Geophysical Research: Biogeosciences*, **117**(G1), G01036, doi:10.1029/2011JG001886.
- Johanson, C.M. and Q. Fu, 2009: Hadley cell widening: model simulations versus observations. *Journal of Climate*, **22**(10), 2713-2725.
- Jöhnk, K.D., J. Huisman, J. Sharples, B. Sommeijer, P.M. Visser, and J.M. Stroom, 2008: Summer heatwaves promote blooms of harmful cyanobacteria. *Global Change Biology*, **14**(3), 495-512.
- Johnson, W.C., B.V. Millett, T. Gilmanov, R.A. Voldseth, G.R. Guntenspergen, and D.E. Naugle, 2005: Vulnerability of northern prairie wetlands to climate change. *Bioscience*, **55**(10), 863-872.
- Johnstone, J.F., T.N. Hollingsworth, F.S. Chapin, and M.C. Mack, 2010: Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. *Global Change Biology*, **16**(4), 1281-1295.
- Jones, C., J. Lowe, S. Liddicoat, and R. Betts, 2009: Committed terrestrial ecosystem changes due to climate change. *Nature Geoscience*, **2**(7), 484-487.
- Jones, C.D., J.K. Hughes, N. Bellouin, S.C. Hardiman, G.S. Jones, J. Knight, S. Liddicoat, F.M. O'Connor, R.J. Andres, C. Bell, K.O. Boo, A. Bozzo, N. Butchart, P. Cadule, K.D. Corbin, M. Doutriaux-Boucher, P. Friedlingstein, J. Gornall, L. Gray, P.R. Halloran, G. Hurtt, W.J. Ingram, J.F. Lamarque, R.M. Law, M. Meinshausen, S. Osprey, E.J. Palin, L.P. Chini, T. Raddatz, M.G. Sanderson, A.A. Sellar, A. Schurer, P. Valdes, N. Wood, S. Woodward, M. Yoshioka, and M. Zerroukat, 2011: The HadGEM2-ES implementation of CMIP5 centennial simulations. *Geoscientific Model Development*, **4**(3), 543-570.
- Jones, M.C., S.R. Dye, J.K. Pinnegar, R. Warren, and W.W.L. Cheung, 2012: Modelling commercial fish distributions: prediction and assessment using different approaches. *Ecological Modelling*, **225**, 133-145.

- Jongman, R.H.G., I.M. Bouwma, A. Griffioen, L. Jones-Walters, and A.M. Van Doorn, 2011:** The Pan European Ecological Network: PEEN. *Landscape Ecology*, **26**(3), 311-326.
- Jonsson, B. and N. Jonsson, 2009:** A review of the likely effects of climate change on anadromous Atlantic salmon *Salmo salar* and brown trout *Salmo trutta*, with particular reference to water temperature and flow. *Journal of Fish Biology*, **75**(10), 2381-2447.
- Jorgenson, M.T., V. Romanovsky, J. Harden, Y. Shur, J. O'Donnell, E.A.G. Schuur, M. Kanevskiy, and S. Marchenko, 2010:** Resilience and vulnerability of permafrost to climate change. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **40**(7), 1219-1236.
- Joubert, D.F., A. Rothauge, and G.N. Smit, 2008:** A conceptual model of vegetation dynamics in the semiarid Highland savanna of Namibia, with particular reference to bush thickening by *Acacia mellifera*. *Journal of Arid Environments*, **72**(12), 2201-2210.
- Jung, M., M. Reichstein, P. Ciais, S.I. Seneviratne, J. Sheffield, M.L. Goulden, G. Bonan, A. Cescatti, J.Q. Chen, R. de Jeu, A.J. Dolman, W. Eugster, D. Gerten, D. Gianelle, N. Gobron, J. Heinke, J. Kimball, B.E. Law, L. Montagnani, Q.Z. Mu, B. Mueller, K. Oleson, D. Papale, A.D. Richardson, O. Rouspard, S. Running, E. Tomelleri, N. Viovy, U. Weber, C. Williams, E. Wood, S. Zaehle, and K. Zhang, 2010:** Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature*, **467**(7318), 951-954.
- Kaiser, K.E., B.L. McGlynn, and R.E. Emanuel, 2012:** Ecohydrology of an outbreak: mountain pine beetle impacts trees in drier landscape positions first. *Ecohydrology*, **6**(3), 444-454.
- Kane, J.M., K.A. Meinhardt, T. Chang, B.L. Cardall, R. Michalet, and T.G. Whitham, 2011:** Drought-induced mortality of a foundation species (*Juniperus monosperma*) promotes positive afterlife effects in understory vegetation. *Plant Ecology*, **212**(5), 733-741.
- Kannah, K.D., J. Beringer, P. North, and L. Hutley, 2012:** Control of atmospheric particles on diffuse radiation and terrestrial plant productivity. *Progress in Physical Geography*, **36**(2), 209-237.
- Kappes, H. and P. Haase, 2012:** Slow, but steady: dispersal of freshwater molluscs. *Aquatic Sciences*, **74**(1), 1-14.
- Karell, P., K. Ahola, T. Karstinen, J. Valkama, and J.E. Brommer, 2011:** Climate change drives microevolution in a wild bird. *Nature Communications*, **2**, 208, doi:10.1038/ncomms1213.
- Karlsson, J., P. Bystrom, J. Ask, P. Ask, L. Persson, and M. Jansson, 2009:** Light limitation of nutrient-poor lake ecosystems. *Nature*, **460**(7254), 506-509.
- Karnosky, D.F., K.S. Pregitzer, D.R. Zak, M.E. Kubiske, G.R. Hendrey, D. Weinstein, M. Nosal, and K.E. Percy, 2005:** Scaling ozone responses of forest trees to the ecosystem level in a changing climate. *Plant Cell and Environment*, **28**(8), 965-981.
- Kasischke, E.S., D.L. Verbyla, T.S. Rupp, A.D. McGuire, K.A. Murphy, R. Jandt, J.L. Barnes, E.E. Hoy, P.A. Duffy, M. Calef, and M.R. Turetsky, 2010:** Alaska's changing fire regime – implications for the vulnerability of its boreal forests. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **40**(7), 1313-1324.
- Kasson, M.T. and W.H. Livingston, 2012:** Relationships among beech bark disease, climate, radial growth response and mortality of American beech in northern Maine, USA. *Forest Pathology*, **42**(3), 199-212.
- Kaufman, D.S., D.P. Schneider, N.P. McKay, C.M. Ammann, R.S. Bradley, K.R. Briffa, G.H. Miller, B.L. Otto-Bliesner, J.T. Overpeck, B.M. Vinther, and Arctic Lakes 2k Project, 2009:** Recent warming reverses long-term arctic cooling. *Science*, **325**(5945), 1236-1239.
- Kaushal, S.S., G.E. Likens, N.A. Jaworski, M.L. Pace, A.M. Sides, D. Seekell, K.T. Belt, D.H. Secor, and R.L. Wingate, 2010:** Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment*, **8**(9), 461-466.
- Kearney, M. and W. Porter, 2009:** Mechanistic niche modelling: combining physiological and spatial data to predict species' ranges. *Ecology Letters*, **12**(4), 334-350.
- Kearney, M., W.P. Porter, C. Williams, S. Ritchie, and A.A. Hoffmann, 2009:** Integrating biophysical models and evolutionary theory to predict climatic impacts on species' ranges: the dengue mosquito *Aedes aegypti* in Australia. *Functional Ecology*, **23**(3), 528-538.
- Kearney, M.R., B.A. Wintle, and W.P. Porter, 2010:** Correlative and mechanistic models of species distribution provide congruent forecasts under climate change. *Conservation Letters*, **3**(3), 203-213.
- Keenan, T., J. Maria Serra, F. Lloret, M. Ninyerola, and S. Sabate, 2011:** Predicting the future of forests in the Mediterranean under climate change, with niche- and process-based models: CO₂ matters! *Global Change Biology*, **17**(1), 565-579.
- Keith, D.A., H.R. Akcakaya, W. Thuiller, G.F. Midgley, R.G. Pearson, S.J. Phillips, H.M. Regan, M.B. Araujo, and T.G. Rebelo, 2008:** Predicting extinction risks under climate change: coupling stochastic population models with dynamic bioclimatic habitat models. *Biology Letters*, **4**(5), 560-563.
- Keith, H., E. van Gorsel, K.L. Jacobsen, and H.A. Cleugh, 2012:** Dynamics of carbon exchange in a Eucalyptus forest in response to interacting disturbance factors. *Agricultural and Forest Meteorology*, **153**, 67-81.
- Ketola, T., V. Kellermann, T.N. Kristensen, and V. Loeschcke, 2012:** Constant, cycling, hot and cold thermal environments: strong effects on mean viability but not on genetic estimates. *Journal of Evolutionary Biology*, **25**(6), 1209-1215.
- Kgope, B.S., W.J. Bond, and G.F. Midgley, 2010:** Growth responses of African savanna trees implicate atmospheric CO₂ as a driver of past and current changes in savanna tree cover. *Austral Ecology*, **35**(4), 451-463.
- Kharuk, V.I., K.J. Ranson, P.A. Oskorbin, S.T. Im, and M.L. Dvinskaya, 2013:** Climate induced birch mortality in Trans-Baikal lake region, Siberia. *Forest Ecology and Management*, **289**, 385-392.
- Kherchouche, D., M. Kalla, E.M. Gutiérrez, S. Attalah, and M. Bouzghaia, 2012:** Impact of droughts on *Cedrus atlantica* forests dieback in the Aurès (Algeria). *Journal of Life Sciences*, **6**, 1262-1269.
- Khoury, C., B. Laliberte, and L. Guarino, 2010:** Trends in *ex situ* conservation of plant genetic resources: a review of global crop and regional conservation strategies. *Genetic Resources and Crop Evolution*, **57**(4), 625-639.
- Kiesecker, J.M., 2011:** Global stressors and the global decline of amphibians: tipping the stress immunocompetency axis. *Ecological Research*, **26**(5), 897-908.
- Kimball, S., A.L. Angert, T.E. Huxman, and D.L. Venable, 2010:** Contemporary climate change in the Sonoran Desert favors cold-adapted species. *Global Change Biology*, **16**(5), 1555-1565.
- Kindermann, G.E., I. McCallum, S. Fritz, and M. Obersteiner, 2008:** A global forest growing stock, biomass and carbon map based on FAO statistics. *Silva Fennica*, **42**(3), 387-396.
- Kinlan, B.P. and S.D. Gaines, 2003:** Propagule dispersal in marine and terrestrial environments: a community perspective. *Ecology*, **84**(8), 2007-2020.
- Kint, V., W. Aertsen, M. Campioli, D. Vansteenkiste, A. Delcloo, and B. Muys, 2012:** Radial growth change of temperate tree species in response to altered regional climate and air quality in the period 1901-2008. *Climatic Change*, **115**(2), 343-363.
- Kirdyanov, A.V., F. Hagedorn, A.A. Knorre, E.V. Fedotova, E.A. Vaganov, M.M. Naurzbaev, P.A. Moiseev, and A. Rigling, 2012:** 20th century tree-line advance and vegetation changes along an altitudinal transect in the Putorana Mountains, northern Siberia. *Boreas*, **41**(1), 56-67.
- Kirilenko, A.P. and R.A. Sedjo, 2007:** Climate change impacts on forestry. *Proceedings of the National Academy of Sciences of the United States of America*, **104**(50), 19697-19702.
- Kirschbaum, M.U.F., S. Sagar, K.R. Tate, D.L. Giltrap, A.-G.E. Ausseil, S. Greenhalgh, and D. Whitehead, 2012:** Comprehensive evaluation of the climate-change implications of shifting land use between forest and grassland: New Zealand as a case study. *Agriculture, Ecosystems & Environment*, **150**, 123-138.
- Kirwan, M.L. and L.K. Blum, 2011:** Enhanced decomposition offsets enhanced productivity and soil carbon accumulation in coastal wetlands responding to climate change. *Biogeosciences*, **8**(4), 987-993.
- Kjøhl, M., A. Nielsen, and N.C. Stenseth, 2011:** *Potential Effects of Climate Change on Crop Pollination*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 38 pp.
- Klanderud, K. and O. Totland, 2005:** Simulated climate change altered dominance hierarchies and diversity of an alpine biodiversity hotspot. *Ecology*, **86**(8), 2047-2054.
- Klausmeyer, K.R. and M.R. Shaw, 2009:** Climate change, habitat loss, protected areas and the climate adaptation potential of species in Mediterranean ecosystems worldwide. *PLoS One*, **4**(7), e6392, doi:10.1371/journal.pone.0006392.
- Klein Goldewijk, K., A. Beusen, and P. Janssen, 2010:** Long term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene*, **20**(4), 565-573.
- Klein Goldewijk, K., A. Beusen, G. van Drecht, and M. de Vos, 2011:** The HYDE 3.1 spatially explicit database of human induced land use change over the past 12,000 years. *Global Ecology and Biogeography*, **20**, 73-86.
- Klingberg, J., M. Engardt, J. Uddling, P.E. Karlsson, and H. Pleijel, 2011:** Ozone risk for vegetation in the future climate of Europe based on stomatal ozone uptake calculations. *Tellus Series A: Dynamic Meteorology and Oceanography*, **63**(1), 174-187.

- Klos, R.J., G.G. Wang, W.L. Bauerle, and J.R. Rieck, 2009: Drought impact on forest growth and mortality in the southeast USA: an analysis using Forest Health and Monitoring data. *Ecological Applications*, **19**(3), 699-708.
- Knapp, A.K., J.M. Briggs, S.L. Collins, S.R. Archer, M.S. Bret-Harte, B.E. Ewers, and D.P. Peters, 2007: Shrub encroachment in North American grasslands: shifts in growth form dominance rapidly alters control of ecosystem carbon inputs. *Global Change Biology*, **14**(3), 615-623.
- Knapp, A.K., C. Beier, D.D. Briske, A.T. Classen, Y. Luo, M. Reichstein, M.D. Smith, S.D. Smith, J.E. Bell, P.A. Fay, J.L. Heisler, S.W. Leavitt, R. Sherry, B. Smith, and E. Weng, 2008: Consequences of more extreme precipitation regimes for terrestrial ecosystems. *Bioscience*, **58**(9), 811-821.
- Knapp, S., I. Kühn, R. Wittig, W.A. Ozinga, P. Poschlod, and S. Klotz, 2008: Urbanization causes shifts in species' trait state frequencies. *Preslia*, **80**(4), 375-388.
- Knapp, S., L. Dinsmore, C. Fissore, S.E. Hobbie, J. Jakobsdottir, J. Kattge, J.R. King, S. Klotz, J.P. McFadden, and J.M. Cavender-Bares, 2012: Phylogenetic and functional characteristics of household yard floras and their changes along an urbanization gradient. *Ecology*, **93**(8 Suppl.), S83-S98.
- Knohl, A. and D.D. Baldocchi, 2008: Effects of diffuse radiation on canopy gas exchange processes in a forest ecosystem. *Journal of Geophysical Research: Biogeosciences*, **113**(G2), G02023, doi:10.1029/2007JG000663.
- Knox, R., G. Bisht, J. Wang, and R. Bras, 2011: Precipitation variability over the forest-to-nonforest transition in southwestern Amazonia. *Journal of Climate*, **24**, 2368-2377.
- Knudsen, E., A. Linden, C. Both, N. Jonzen, F. Pulido, N. Saino, W.J. Sutherland, L.A. Bach, T. Coppack, T. Ergon, P. Gienapp, J.A. Gill, O. Gordo, A. Hedenstrom, E. Lehtikoinen, P.P. Marra, A.P. Moller, A.L.K. Nilsson, G. Peron, E. Ranta, D. Rubolini, T.H. Sparks, F. Spina, C.E. Studds, S.A. Saether, P. Tryjanowski, and N.C. Stenseth, 2011: Challenging claims in the study of migratory birds and climate change. *Biological Reviews*, **86**(4), 928-946.
- Knutti, R. and J. Sedláček, 2012: Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, **3**, 369-373.
- Koehler, I.H., P.R. Poulton, K. Auerswald, and H. Schnyder, 2010: Intrinsic water-use efficiency of temperate seminatural grassland has increased since 1857: an analysis of carbon isotope discrimination of herbage from the Park Grass Experiment. *Global Change Biology*, **16**(5), 1531-1541.
- Kollár, J., P. Hrubík, and S. Tkáčová, 2009: Monitoring of harmful insect species in urban conditions in selected model areas of Slovakia. *Plant Protection Science*, **45**, 119-124.
- Kollberg, I., H. Bylund, A. Schmidt, J. Gershenson, and C. Björkman, 2013: Multiple effects of temperature, photoperiod and food quality on the performance of a pine sawfly. *Ecological Entomology*, **38**(2), 201-208.
- Konarzewski, T.K., B.R. Murray, and R.C. Godfree, 2012: Rapid development of adaptive, climate-driven clinal variation in seed mass in the invasive annual forb *Echium plantagineum* L. *PLoS One*, **7**(12), e49000, doi:10.1371/journal.pone.0049000.
- Kongstad, J., I.K. Schmidt, T. Riis-Nielsen, M.F. Arndal, T.N. Mikkelsen, and C. Beier, 2012: High resilience in heathland plants to changes in temperature, drought, and CO₂ in combination: results from the CLIMAITE Experiment. *Ecosystems*, **15**(2), 269-283.
- Körner, C. and D. Basler, 2010: Phenology under global warming. *Science*, **327**(5972), 1461-1462.
- Körner, C., J.A. Morgan, and R. Norby, 2007: CO₂ fertilisation: when, where, how much? In: *Terrestrial Ecosystems in a Changing World* [Canadell, S.G., D.E. Pataki, and L.F. Pitelka (eds.)]. Springer, Berlin Heidelberg, Germany, pp. 9-22.
- Koutavas, A., 2008: Late 20th century growth acceleration in greek firs (*Abies cephalonica*) from Cephalonia Island, Greece: a CO₂ fertilization effect? *Dendrochronologia*, **26**(1), 13-19.
- Kovach-Orr, C. and G.F. Fussmann, 2013: Evolutionary and plastic rescue in multitrophic model communities. *Philosophical Transactions of the Royal Society B*, **368**(1610), 20120084, doi:10.1098/rstb.2012.0084.
- Koven, C.D., W.J. Riley, and A. Stern, 2013: Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 Earth System Models. *Journal of Climate*, **26**(6), 1877-1900.
- Kraft, N.J.B., M.R. Metz, R.S. Condit, and J. Chave, 2010: The relationship between wood density and mortality in a global tropical forest data set. *New Phytologist*, **188**(4), 1124-1136.
- Kramer, K., B. Degen, J. Buschbom, T. Hickler, W. Thuiller, M.T. Sykes, and W. de Winter, 2010: Modelling exploration of the future of European beech (*Fagus sylvatica* L.) under climate change – range, abundance, genetic diversity and adaptive response. *Forest Ecology and Management*, **259**(11), 2213-2222.
- Kramer, K., R.J. Bijlsma, T. Hickler, and W. Thuiller, 2012: Why would plant species become extinct locally if growing conditions improve? *International Journal of Biological Sciences*, **8**(8), 1121-1129.
- Kremer, A., O. Ronce, J.J. Robledo-Arnuncio, F. Guillaume, G. Bohrer, R. Nathan, J.R. Bridle, R. Gomulkiewicz, E.K. Klein, K. Ritland, A. Kuparinen, S. Gerber, and S. Schueler, 2012: Long-distance gene flow and adaptation of forest trees to rapid climate change. *Ecology Letters*, **15**(4), 378-392.
- Kriegler, E., J.W. Hall, H. Held, R. Dawson, and H.J. Schellnhuber, 2009: Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(13), 5041-5046.
- Kropelin, S., D. Verschuren, A.M. Lezine, H. Eggermont, C. Cocquyt, P. Francus, J.P. Cazet, M. Fagot, B. Rumes, J.M. Russell, F. Darius, D.J. Conley, M. Schuster, H. von Suchodoletz, and D.R. Engstrom, 2008: Climate-driven ecosystem succession in the Sahara: the past 6000 years. *Science*, **320**(5877), 765-768.
- Kudo, G., Y. Amagai, B. Hoshino, and M. Kaneko, 2011: Invasion of dwarf bamboo into alpine snow-meadows in northern Japan: pattern of expansion and impact on species diversity. *Ecology and Evolution*, **1**(1), 85-96.
- Kuhlmann, M., D. Guo, R. Veldtman, and J. Donaldson, 2012: Consequences of warming up a hotspot: species range shifts within a centre of bee diversity. *Diversity and Distributions*, **18**(9), 885-897.
- Kukowski, K., S. Schwinning, and B. Schwartz, 2013: Hydraulic responses to extreme drought conditions in three co-dominant tree species in shallow soil over bedrock. *Oecologia*, **171**(4), 819-830.
- Kuldna, P., K. Peterson, H. Poltimae, and J. Luig, 2009: An application of DPSIR framework to identify issues of pollinator loss. *Ecological Economics*, **69**(1), 32-42.
- Kullman, L. and L. Öberg, 2009: Post-Little Ice Age tree line rise and climate warming in the Swedish Scandes: a landscape ecological perspective. *Journal of Ecology*, **97**(3), 415-429.
- Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen, and I.A. Shiklomanov, 2007: Freshwater resources and their management. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 173-210.
- Kuparinen, A., O. Savolainen, and F.M. Schurr, 2010: Increased mortality can promote evolutionary adaptation of forest trees to climate change. *Forest Ecology and Management*, **259**(5), 1003-1008.
- Kurz, W.A., C.C. Dymond, G. Stinson, G.J. Rampley, E.T. Neilson, A.L. Carroll, T. Ebata, and L. Safranyik, 2008: Mountain pine beetle and forest carbon feedback to climate change. *Nature*, **452**(7190), 987-990.
- Kusano, T. and M. Inoue, 2008: Long-term trends toward earlier breeding of Japanese amphibians. *Journal of Herpetology*, **42**(4), 608-614.
- Kuusaaari, M., R. Bommarco, R.K. Heikkinen, A. Helm, J. Krauss, R. Lindborg, E. Ockinger, M. Partel, J. Pino, F. Roda, C. Stefanescu, T. Teder, M. Zobel, and I. Steffan-Dewenter, 2009: Extinction debt: a challenge for biodiversity conservation. *Trends in Ecology & Evolution*, **24**(10), 564-571.
- Kvalevåg, M.M. and G. Myhre, 2007: Human impact on direct and diffuse solar radiation during the industrial era. *Journal of Climate*, **20**(19), 4874-4883.
- Lambert, A.M., A.J. Miller-Rushing, and D.W. Inouye, 2010: Changes in snowmelt date and summer precipitation affect the flowering phenology of *Erythronium grandiflorum* (Glacier Lily; Liliaceae). *American Journal of Botany*, **97**(9), 1431-1437.
- Lambin, E.F. and P. Meyfroidt, 2011: Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America*, **108**(9), 3465-3472.
- Lane, J.E., L.E.B. Kruuk, A. Charmantier, J.O. Murie, and F.S. Dobson, 2012: Delayed phenology and reduced fitness associated with climate change in a wild hibernator. *Nature*, **489**(7417), 554-557.
- Langan, S.J., L. Johnston, M.J. Donaghy, A.F. Youngson, D.W. Hay, and C. Soulsby, 2001: Variation in river water temperatures in an upland stream over a 30-year period. *Science of the Total Environment*, **265**(1-3), 195-207.
- Langley, J.A. and J.P. Megonigal, 2010: Ecosystem response to elevated CO₂ levels limited by nitrogen-induced plant species shift. *Nature*, **466**(7302), 96-99.
- Lantz, T.C., S.V. Kokelj, S.E. Gergel, and G.H.R. Henry, 2009: Relative impacts of disturbance and temperature: persistent changes in microenvironment and vegetation in retrogressive thaw slumps. *Global Change Biology*, **15**(7), 1664-1675.

- Lantz, T.C., S.E. Gergel, and G.H.R. Henry, 2010: Response of green alder (*Alnus viridis* subsp. *fruticosa*) patch dynamics and plant community composition to fire and regional temperature in north-western Canada. *Journal of Biogeography*, **37**(8), 1597-1610.
- Lapola, D.M., M.D. Oyama, and C.A. Nobre, 2009: Exploring the range of climate biome projections for tropical South America: the role of CO₂ fertilization and seasonality. *Global Biogeochemical Cycles*, **23**(3), GB3003, doi:10.1029/2008GB003357.
- Lapola, D.M., R. Schaldach, J. Alcamo, A. Bondeau, J. Koch, C. Koelking, and J.A. Priess, 2010: Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(8), 3388-3393.
- Larsen, K.S., L.C. Andresen, C. Beier, S. Jonasson, K.R. Albert, P. Ambus, M.F. Arndal, M.S. Carter, S. Christensen, M. Holmstrup, A. Ibrom, J. Kongstad, L. van der Linden, K. Maraldo, A. Michelsen, T.N. Mikkelsen, K. Pilegaard, A. Prieme, H. Røpoulsen, I.K. Schmidt, M.B. Selsted, and K. Stevnbak, 2011: Reduced N cycling in response to elevated CO₂, warming, and drought in a Danish heathland: synthesizing results of the CLIMATE project after two years of treatments. *Global Change Biology*, **17**(5), 1884-1899.
- Laurance, W.F., D.C. Useche, L.P. Shoo, S.K. Herzog, M. Kessler, F. Escobar, G. Brehm, J.C. Axmacher, I.C. Chen, L.A. Gamez, P. Hietz, K. Fiedler, T. Pycrz, J. Wolf, C.L. Merkord, C. Cardelus, A.R. Marshall, C. Ah-Peng, G.H. Aplet, M.D. Arizmendi, W.J. Baker, J. Barone, C.A. Bruhl, R.W. Bussmann, D. Cizuzza, G. Eilu, M.E. Favila, A. Hemp, C. Hemp, J. Homeier, J. Hurtado, J. Jankowski, G. Kattan, J. Kluge, T. Kromer, D.C. Lees, M. Lehnert, J.T. Longino, J. Lovett, P.H. Martin, B.D. Patterson, R.G. Pearson, K.S.H. Peh, B. Richardson, M. Richardson, M.J. Samways, F. Senbeta, T.B. Smith, T.M.A. Utteridge, J.E. Watkins, R. Wilson, S.E. Williams, and C.D. Thomas, 2011: Global warming, elevational ranges and the vulnerability of tropical biota. *Biological Conservation*, **144**(1), 548-557.
- Lavergne, S., N. Mouquet, W. Thuiller, and O. Ronce, 2010: Biodiversity and climate change: integrating evolutionary and ecological responses of species and communities. *Annual Review of Ecology, Evolution, and Systematics*, **41**, 321-350.
- Lavergne, S., M.E.K. Evans, I.J. Burfield, F. Jiguet, and Thuiller, W., 2013: Are species' responses to global change predicted by past niche evolution? *Philosophical Transactions of the Royal Society B*, **368**(1610), 20120091, doi:10.1098/rstb.2012.0091.
- Lawrence, D.M. and S.C. Swenson, 2011: Permafrost response to increasing Arctic shrub abundance depends on the relative influence of shrubs on local soil cooling versus large-scale climate warming. *Environmental Research Letters*, **6**(4), 045504, doi:10.1088/1748-9326/6/4/045504.
- Lawrence, D.M., P.E. Thornton, K.W. Oleson, and G.B. Bonan, 2007: The partitioning of evapotranspiration into transpiration, soil evaporation, and canopy evaporation in a GCM: impacts on land-atmosphere interaction. *Journal of Hydrometeorology*, **8**, 862-880.
- Lawson, C.R., J.J. Bennie, C.D. Thomas, J.A. Hodgson, and R.J. Wilson, 2012: Local and landscape management of an expanding range margin under climate change. *Journal of Applied Ecology*, **49**, 552-561.
- Le Conte, Y. and M. Navajas, 2008: Climate change: impact on honey bee populations and diseases. *Revue Scientifique Et Technique – Office International Des Epizooties*, **27**(2), 499-510.
- Le Quéré, C., M.R. Raupach, J.G. Canadell, and G. Marland, 2009: Trends in the sources and sinks of carbon dioxide. *Nature Geoscience*, **2**(12), 831-836.
- Le Quéré, C., R.J. Andres, T. Boden, T. Conway, R.A. Houghton, J.I. House, G. Marland, G.P. Peters, G. van der Werf, A. Ahlström, R.M. Andrew, L. Bopp, J.G. Canadell, P. Ciais, S.C. Doney, C. Enright, P. Friedlingstein, C. Huntingford, A.K. Jain, C. Jourdain, E. Kato, R.F. Keeling, K. Klein Goldewijk, S. Levis, P. Levy, M. Lomas, B. Poulter, M.R. Raupach, J. Schwinger, S. Sitch, B.D. Stocker, N. Viovy, S. Zaehle, and N. Zeng, 2012: The global carbon budget 1959-2011. *Earth System Science Data*, **5**(2), 1107-1157.
- Leadley, P., H.N. Pereira, R. Alkemade, J.F. Fernandez-Manjarrés, V. Proença, J.P.W. Scharlemann, and M.J. Walpole, 2010: *Biodiversity Scenarios: Projections of 21st Century Change in Biodiversity and Associated Ecosystem Services*. A Technical Report for the Global Biodiversity Outlook 3, Technical Series No. 50, Secretariat of the Convention on Biological Diversity, Montreal, Canada, 132 pp.
- Leakey, A.D.B., E.A. Ainsworth, C.J. Bernacchi, A. Rogers, S.P. Long, and D.R. Ort, 2009: Elevated CO₂ effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany*, **60**(10), 2859-2876.
- Leal, M. and A.R. Gunderson, 2012: Rapid change in the thermal tolerance of a tropical lizard. *American Naturalist*, **180**(6), 815-822.
- Ledger, M.E., L.E. Brown, F.K. Edwards, A.M. Milner, and G. Woodward, 2013: Drought alters the structure and functioning of complex food webs. *Nature Climate Change*, **3**(3), 223-227.
- Lee, M., P. Manning, J. Rist, S.A. Power, and C. Marsh, 2010: A global comparison of grassland biomass responses to CO₂ and nitrogen enrichment. *Philosophical Transactions of the Royal Society B*, **365**(1549), 2047-2056.
- Leishman, M.R., T. Haslehurst, A. Ares, and Z. Baruch, 2007: Leaf trait relationships of native and invasive plants: community- and global-scale comparisons. *New Phytologist*, **176**(3), 635-643.
- Lenihan, J.M., D. Bachelet, R.P. Neilson, and R. Drapek, 2008: Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. *Climatic Change*, **87**, S215-S230.
- Lenoir, J., J.C. Gegout, P.A. Marquet, P. de Ruffray, and H. Brisse, 2008: A significant upward shift in plant species optimum elevation during the 20th century. *Science*, **320**(5884), 1768-1771.
- Lenoir, J., J.C. Gegout, J.L. Dupouey, D. Bert, and J.C. Svenning, 2010: Forest plant community changes during 1989-2007 in response to climate warming in the Jura Mountains (France and Switzerland). *Journal of Vegetation Science*, **21**(5), 949-964.
- Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber, 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **105**(6), 1786-1793.
- Leonelli, G., M. Pelfini, U. Morra di Cella, and V. Garavaglia, 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.
- Lermen, D., B. Blomeke, R. Browne, A. Clarke, P.W. Dyce, T. Fixemer, G.R. Fuhr, W.V. Holt, K. Jewgenow, R.E. Lloyd, S. Lotters, M. Paulus, G.M. Reid, D.H. Rapoport, D. Rawson, J. Ringleb, O.A. Ryder, G. Sporn, T. Schmitt, M. Veith, and P. Muller, 2009: Cryobanking of viable biomaterials: implementation of new strategies for conservation purposes. *Molecular Ecology*, **18**(6), 1030-1033.
- Leuning, R., 1995: A critical appraisal of a combined stomatal-photosynthesis model for C₃ plants. *Plant, Cell and Environment*, **18**, 339-355.
- Leuzinger, S. and C. Körner, 2010: Rainfall distribution is the main driver of runoff under future CO₂-concentration in a temperate deciduous forest. *Global Change Biology*, **16**(1), 246-254.
- Leuzinger, S., Y.Q. Luo, C. Beier, W. Dieleman, S. Vicca, and C. Körner, 2011: Do global change experiments overestimate impacts on terrestrial ecosystems? *Trends in Ecology & Evolution*, **26**(5), 236-241.
- Levis, S., 2010: Modeling vegetation and land use in models of the Earth System. *Wiley Interdisciplinary Reviews: Climate Change*, **1**(6), 840-856.
- Lewis, S.L., J. Lloyd, S. Sitch, E.T.A. Mitchard, and W.F. Laurance, 2009a: Changing ecology of tropical forests: evidence and drivers. *Annual Review of Ecology Evolution and Systematics*, **40**, 529-549.
- Lewis, S.L., G. Lopez-Gonzalez, B. Sonke, K. Affum-Baffoe, T.R. Baker, L.O. Ojo, O.L. Phillips, J.M. Reitsma, L. White, J.A. Comiskey, M.N. Djukouo, C.E.N. Ewango, T.R. Feldpausch, A.C. Hamilton, M. Gloor, T. Hart, A. Hladik, J. Lloyd, J.C. Lovett, J.R. Makana, Y. Malhi, F.M. Mbago, H.J. Ndangalasi, J. Peacock, K.S.H. Peh, D. Sheil, T. Sunderland, M.D. Swaine, J. Taplin, D. Taylor, S.C. Thomas, R. Votere, and H. Wöll, 2009b: Increasing carbon storage in intact African tropical forests. *Nature*, **457**, 1003-1007.
- Lewis, S.L., P.M. Brando, O.L. Phillips, G.M.F. van der Heijden, and D. Nepstad, 2011: The 2010 Amazon drought. *Science*, **331**(6017), 554.
- Li, D.Z. and H.W. Pritchard, 2009: The science and economics of *ex situ* plant conservation. *Trends in Plant Science*, **14**(11), 614-621.
- Li, W.H., R.E. Dickinson, R. Fu, G.Y. Niu, Z.L. Yang, and J.G. Canadell, 2007: Future precipitation changes and their implications for tropical peatlands. *Geophysical Research Letters*, **34**, L01403, doi:10.1029/2006GL028364.
- Li, Z., W.-z. Liu, X.-c. Zhang, and F.-l. Zheng, 2009: Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology*, **377**(1-2), 35-42.
- Liao, J.D., T.W. Boutton, and J.D. Jastrow, 2006: Storage and dynamics of carbon and nitrogen in soil physical fractions following woody plant invasion of grassland. *Soil Biology and Biochemistry*, **38**(11), 3184-3196.
- Liljedahl, A., L. Hinzman, R. Busey, and K. Yoshikawa, 2007: Physical short-term changes after a tussock tundra fire, Seward Peninsula, Alaska. *Journal of Geophysical Research: Earth Surface*, **112**(F2), F02S07, doi:10.1029/2006JF000554.

- Limpens, J., F. Berendse, C. Blodau, J.G. Canadell, C. Freeman, J. Holden, N. Roulet, H. Rydin, and G. Schaeppman-Strub, 2008: Peatlands and the carbon cycle: from local processes to global implications – a synthesis. *Biogeosciences*, **5**(5), 1475-1491.
- Limpens, J., G. Granath, U. Gunnarsson, R. Aerts, S. Bayley, L. Bragazza, J. Bubier, A. Buttler, L.J.L. van den Berg, A.J. Francez, R. Gerdol, P. Grosvernier, M. Heijmans, M.R. Hoosbeek, S. Hotes, M. Ilomets, I. Leith, E.A.D. Mitchell, T. Moore, M.B. Nilsson, J.F. Nordbakken, L. Rochefort, H. Rydin, L.J. Sheppard, M. Thormann, M.M. Wiedermann, B.L. Williams, and B. Xu, 2011: Climatic modifiers of the response to nitrogen deposition in peat-forming Sphagnum mosses: a meta-analysis. *New Phytologist*, **191**(2), 496-507.
- Linares, J.C., J.J. Camarero, and J.A. Carreira, 2009: Interacting effects of changes in climate and forest cover on mortality and growth of the southernmost European fir forests. *Global Ecology and Biogeography*, **18**(4), 485-497.
- Linares, J.C., P.A. Tiscar, J.J. Camarero, L. Taiqui, and B. Viñepla, 2011: Tree growth decline on relict western-Mediterranean mountain forests: causes and impacts. In: *Forest Decline: Causes and Impacts* [Jenkins, J.A.(ed)]. Nova Publishers, New York, NY, USA, pp. 91-110.
- Lindner, M., M. Maroschek, S. Netherer, A. Kremer, A. Barbat, J. Garcia-Gonzalo, R. Seidl, S. Delzon, P. Corona, M. Kolstrom, M.J. Lexer, and M. Marchetti, 2010: Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, **259**(4), 698-709.
- Lindroth, R.L., 2010: Impacts of elevated atmospheric CO₂ and O₃ on forests: phytochemistry, trophic interactions, and ecosystem dynamics. *Journal of Chemical Ecology*, **36**(1), 2-21.
- Lips, K.R., J. Diffendorfer, J.R. Mendelson, and M.W. Sears, 2008: Riding the wave: reconciling the roles of disease and climate change in amphibian declines. *PLoS Biology*, **6**(3), 441-454.
- Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling, 2009: Climate and wildfire area burned in western U.S. ecoregions, 1916-2003. *Ecological Applications*, **19**, 1003-1021.
- Littell, J.S., E.E. Oneil, D. McKenzie, J.A. Hicke, J.A. Lutz, R.A. Norheim, and M.M. Elsner, 2010: Forest ecosystems, disturbance, and climatic change in Washington State, USA. *Climatic Change*, **102**(1-2), 129-158.
- Liu, H., A. Park Williams, C. Allen, D. Guo, X. Wu, O.A. Anenkhonov, E. Liang, D.V. Sandanov, Y. Yin, Z. Qi, and N.K. Badmaeva, 2013: Rapid warming accelerates tree growth decline in semi-arid forests of Inner Asia. *Global Change Biology*, **19**(8), 2500-2510.
- Liu, W., Z. Zhang, and S. Wan, 2009: Predominant role of water in regulating soil and microbial respiration and their responses to climate change in a semiarid grassland. *Global Change Biology*, **15**(1), 184-195.
- Livingstone, D.M. and R. Adrian, 2009: Modeling the duration of intermittent ice cover on a lake for climate-change studies. *Limnology and Oceanography*, **54**(5), 1709-1722.
- Lloyd, A.H. and C.L. Fastie, 2003: Recent changes in tree line forest distribution and structure in interior Alaska. *Ecoscience*, **10**, 176-185.
- Lloyd, A.H., A.G. Bunn, and L. Berner, 2011: A latitudinal gradient in tree growth response to climate warming in the Siberian taiga. *Global Change Biology*, **17**(5), 1935-1945.
- Lloyd, J. and G.D. Farquhar, 2008: Effects of rising temperatures and CO₂ on the physiology of tropical forest trees. *Philosophical Transactions of the Royal Society B*, **363**(1498), 1811-1817.
- Loader, N.J., R.P.D. Walsh, I. Robertson, K. Bidin, R.C. Ong, G. Reynolds, D. McCarroll, M. Gagen, and G.H.F. Young, 2011: Recent trends in the intrinsic water-use efficiency of ringless rainforest trees in Borneo. *Philosophical Transactions of the Royal Society B*, **366**(1582), 3330-3339.
- Loarie, S.R., P.B. Duffy, H. Hamilton, G.P. Asner, C.B. Field, and D.D. Ackerly, 2009: The velocity of climate change. *Nature*, **462**, 1052-1055.
- Loarie, S.R., D.B. Lobell, G.P. Asner, Q. Mu, and C.B. Field, 2011: Direct impacts on local climate of sugar-cane expansion in Brazil. *Nature Climate Change*, **1**(2), 105-109.
- Lobell, D.B., W. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science*, **333**(6042), 616-620.
- Long, S.P., E.A. Ainsworth, A. Rogers, and D.R. Ort, 2004: Rising atmospheric carbon dioxide: plants FACE the future. *Annual Review of Plant Biology*, **55**(1), 591-628.
- Longobardi, P., A. Montenegro, H. Beltrami, and M. Eby, 2012: Spatial scale dependency of the modelled climatic response to deforestation. *Biogeosciences Discussions*, **9**, 14639-14687.
- Lopez-Vaamonde, C., D. Agassiz, S. Augustin, J. De Prins, W. De Prins, S. Gomboc, P. Ivinskis, O. Karsholt, A. Koutroumpas, F. Koutroumpa, Z. Laštůvka, E. Marabuto, E. Olivella, L. Przybyłowicz, A. Roques, N. Ryrholm, H. Šefrová, P. Šima, I. Sims, S. Sinev, B. Skulev, R. Tomov, A. Zilli, and D. Lees, 2010: Lepidoptera. In: *Biorisk, Vol. 4, Part 2: Alien Terrestrial Arthropods of Europe* [Roques, A., M. Kenis, D. Lees, C. Lopez-Vaamonde, W. Rabitsch, J.-Y. Rasplus, and D.B. Roy (eds.)]. Pensoft Publishers, Sofia, Bulgaria, pp. 603-668.
- Loreau, M., N. Mouquet, and R.D. Holt, 2003: Meta-ecosystems: a theoretical framework for a spatial ecosystem ecology. *Ecology Letters*, **6**(8), 673-679.
- Lorenzen, E.D., D. Nogues-Bravo, L. Orlando, J. Weinstock, J. Binladen, K.A. Marske, A. Ugan, M.K. Borregaard, M.T.P. Gilbert, R. Nielsen, S.Y.W. Ho, T. Goebel, K.E. Graf, D. Byers, J.T. Stenderup, M. Rasmussen, P.F. Campos, J.A. Leonard, K.P. Koepfli, D. Froese, G. Zazula, T.W. Stafford, K. Aaris-Sorensen, P. Batra, A.M. Haywood, J.S. Singarayer, P.J. Valdes, G. Boeskorov, J.A. Burns, S.P. Davydov, J. Haile, D.L. Jenkins, P. Kosintsev, T. Kuznetsova, X.L. Lai, L.D. Martin, H.G. McDonald, D. Mol, M. Meldgaard, K. Munch, E. Stephan, M. Sablin, R.S. Sommer, T. Sipko, E. Scott, M.A. Suchard, A. Tikhonov, R. Willerslev, R.K. Wayne, A. Cooper, M. Hofreiter, A. Sher, B. Shapiro, C. Rahbek, and E. Willerslev, 2011: Species-specific responses of Late Quaternary megafauna to climate and humans. *Nature*, **479**, 359-364.
- Loss, S.R., L.A. Terwilliger, and A.C. Peterson, 2011: Assisted colonization: integrating conservation strategies in the face of climate change. *Biological Conservation*, **144**(1), 92-100.
- Loustau, D., 2010: *Forests, Carbon Cycle and Climate Change*. Éditions Quae, Versailles, France, 350 pp.
- Lu, C.Q., H.Q. Tian, M.L. Liu, W. Ren, X.F. Xu, G.S. Chen, and C. Zhang, 2012: Effect of nitrogen deposition on China's terrestrial carbon uptake in the context of multifactor environmental changes. *Ecological Applications*, **22**(1), 53-75.
- Lu, J., C. Deser, and T. Reichler, 2009: Cause of the widening of the tropical belt since 1958. *Geophysical Research Letters*, **36**, L03803, doi:10.1029/2008GL036076.
- Luckman, B. and T. Kavanagh, 2000: Impact of climate fluctuations on mountain environments in the Canadian Rockies. *AMBIO: A Journal of the Human Environment*, **29**(7), 371-380.
- Lunt, I.D., L.M. Winsemius, S.P. McDonald, J.W. Morgan, and R.L. Dehaan, 2010: How widespread is woody plant encroachment in temperate Australia? Changes in woody vegetation cover in lowland woodland and coastal ecosystems in Victoria from 1989 to 2005. *Journal of Biogeography*, **37**(4), 722-732.
- Luo, Y.Q., 2007: Terrestrial carbon-cycle feedback to climate warming. *Annual Review of Ecology and Systematics*, **38**, 683-712.
- Luo, Y.Q., D. Gerten, G. Le Maire, W.J. Parton, E.S. Weng, X.H. Zhou, C. Keough, C. Beier, P. Ciais, W. Cramer, J.S. Dukes, B. Emmett, P.J. Hanson, A. Knapp, S. Linder, D. Nepstad, and L. Rustad, 2008: Modeled interactive effects of precipitation, temperature, and CO₂ on ecosystem carbon and water dynamics in different climatic zones. *Global Change Biology*, **14**(9), 1986-1999.
- Luyssaert, S., P. Ciais, S.L. Piao, E.D. Schulze, M. Jung, S. Zaehle, M.J. Schelhaas, M. Reichstein, G. Churkina, D. Papale, G. Abril, C. Beer, J. Grace, D. Loustau, G. Matteucci, F. Marnani, G.J. Nabuurs, H. Verbeeck, M. Sulkava, G.R. Van Der Werf, I.A. Janssens, and Members of the CarboEurope-IP Synthesis Team, 2010: The European carbon balance. 3: forests. *Global Change Biology*, **16**(5), 1429-1450.
- Lydeard, C., R.H. Cowie, W.F. Ponder, A.E. Bogan, P. Bouchet, S.A. Clark, K.S. Cummings, T.J. Frest, O. Gargominy, D.G. Herbert, R. Hershler, K.E. Perez, B. Roth, M. Seddon, E.E. Strong, and F.G. Thompson, 2004: The global decline of non-marine mollusks. *BioScience*, **54**(4), 321-330.
- Ma, L.N., X.T. Lu, Y. Liu, J.X. Guo, N.Y. Zhang, J.Q. Yang, and R.Z. Wang, 2011: The effects of warming and nitrogen addition on soil nitrogen cycling in a temperate grassland, Northeastern China. *PLoS One*, **6**(11), e27645, doi:10.1371/journal.pone.0027645.
- Ma, T. and C.G. Zhou, 2012: Climate-associated changes in spring plant phenology in China. *International Journal of Biometeorology*, **56**(2), 269-275.
- Ma, Z., C. Peng, Q. Zhu, H. Chen, G. Yu, W.H. Li, X. Zhou, W. Wang, and W. Zhang, 2012: Regional drought-induced reduction in the biomass carbon sink of Canada's boreal forests. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(7), 2423-2427.
- MacDonald, G.M., 2010: Global warming and the Arctic: a new world beyond the reach of the Grinnellian niche? *The Journal of Experimental Biology*, **213**, 855-861.
- MacDonald, G.M., K.D. Bennett, S.T. Jackson, L. Parducci, F.A. Smith, J.P. Smol, and K.J. Willis, 2008: Impacts of climate change on species, populations and communities: palaeobiogeographical insights and frontiers. *Progress in Physical Geography*, **32**(2), 139-172.

- Macedo, M.N., R.S. DeFries, D.C. Morton, C.M. Stickler, G.L. Galford, and Y.E. Shimabukuro, 2012:** Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. *Proceedings of the National Academy of Sciences of the United States of America*, **109(4)**, 1341-1346.
- Macias Fauria, M. and E.A. Johnson, 2008:** Climate and wildfires in the North American boreal forest. *Philosophical Transactions of the Royal Society B*, **363(1501)**, 2317-2329.
- Mack, M.C., K.K. Treseder, K.L. Manies, J.W. Harden, E.A.G. Schuur, J.G. Vogel, J.T. Randerson, and F.S. Chapin, 2008:** Recovery of aboveground plant biomass and productivity after fire in mesic and dry black spruce forests of interior Alaska. *Ecosystems*, **11(2)**, 209-225.
- Mack, M.C., M.S. Bret-Harte, T.N. Hollingsworth, R.R. Jandt, E.A.G. Schuur, G.R. Shaver, and D.L. Verbyla, 2011:** Carbon loss from an unprecedented Arctic tundra wildfire. *Nature*, **475(7357)**, 489-492.
- Mackelprang, R., M.P. Waldrop, K.M. DeAngelis, M.M. David, K.L. Chavarria, S.J. Blazewicz, E.M. Rubin, and J.K. Jansson, 2011:** Metagenomic analysis of a permafrost microbial community reveals a rapid response to thaw. *Nature*, **480(7377)**, 368-371.
- Maclachlan, J.S., J.J. Hellmann, and M.W. Schwarz, 2007:** A framework for debate of assisted migration in an era of climate change. *Conservation Biology*, **21(2)**, 297-302.
- Magalhães, M.F., P. Beja, I.J. Schlosser, and M.J. Collares-Pereira, 2007:** Effects of multi-year droughts on fish assemblages of seasonally drying Mediterranean streams. *Freshwater Biology*, **52(8)**, 1494-1510.
- Magnani, F., M. Mencuccini, M. Borghetti, P. Berbigier, F. Berninger, S. Delzon, A. Grelle, P. Hari, P.G. Jarvis, P. Kolari, A.S. Kowalski, H. Lankreijer, B.E. Law, A. Lindroth, D. Loustau, G. Manca, J.B. Moncrieff, M. Rayment, V. Tedeschi, R. Valentini, and J. Grace, 2007:** The human footprint in the carbon cycle of temperate and boreal forests. *Nature*, **447(7146)**, 848-850.
- Mainka, S.A. and G.W. Howard, 2010:** Climate change and invasive species: double jeopardy. *Integrative Zoology*, **5(2)**, 102-111.
- Maiorano, L., A. Faluccci, N.E. Zimmermann, A. Psomas, J. Pottier, D. Baisero, C. Rondinini, A. Guisan, and L. Boitani, 2011:** The future of terrestrial mammals in the Mediterranean basin under climate change. *Philosophical Transactions of the Royal Society B*, **366(1578)**, 2681-2692.
- Malcolm, J.R., C.R. Liu, R.P. Neilson, L. Hansen, and L. Hannah, 2006:** Global warming and extinctions of endemic species from biodiversity hotspots. *Conservation Biology*, **20(2)**, 538-548.
- Malhi, Y., J.T. Roberts, R.A. Betts, T.J. Killeen, W. Li, and C.A. Nobre, 2008:** Climate change, deforestation, and the fate of the Amazon. *Science*, **319(5860)**, 169-172.
- Malhi, Y., L.E.O.C. Aragao, D. Galbraith, C. Huntingford, R. Fisher, P. Zelazowski, S. Sitch, C. McSweeney, and P. Meir, 2009a:** Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America*, **106(49)**, 20610-20615.
- Malhi, Y., L. Aragao, D.B. Metcalfe, R. Paiva, C.A. Quesada, S. Almeida, L. Anderson, P. Brando, J.Q. Chambers, A.C.L. da Costa, L.R. Hutyra, P. Oliveira, S. Patino, E.H. Pyle, A.L. Robertson, and L.M. Teixeira, 2009b:** Comprehensive assessment of carbon productivity, allocation and storage in three Amazonian forests. *Global Change Biology*, **15(5)**, 1255-1274.
- Malmqvist, B., S.D. Rundle, A.P. Covich, A.G. Hildrew, C.T. Robinson, and C.R. Townsend, 2008:** Prospects for streams and rivers: an ecological perspective. In: *Aquatic Ecosystems: Trends and Global Prospects* [Polunin, N.V.C. (ed.)]. Cambridge University Press, Cambridge, UK, pp. 19-29.
- Maniatis, D., Y. Malhi, L.S. Andre, D. Mollicone, N. Barbier, S. Saatchi, M. Henry, L. Tellier, M. Schwartzberg, and M. White, 2011:** Evaluating the potential of commercial forest inventory data to report on forest carbon stock and forest carbon stock changes for REDD+ under the UNFCCC. *International Journal of Forestry Research*, **2011**, 134526, doi:10.1155/2011/134526.
- Mann, D.H., T.S. Rupp, M.A. Olson, and P.A. Duffy, 2012:** Is Alaska's boreal forest now crossing a major ecological threshold? *Arctic Antarctic and Alpine Research*, **44(3)**, 319-331.
- Maraldo, K., I.K. Schmidt, C. Beier, and M. Holmstrup, 2008:** Can field populations of the enchytraeid, *Cognettia sphagnetorum*, adapt to increased drought stress? *Soil Biology & Biochemistry*, **40(7)**, 1765-1771.
- Marengo, J.A., J. Tomasella, L.M. Alves, W.R. Soares, and D.A. Rodriguez, 2011:** The drought of 2010 in the context of historical droughts in the Amazon region. *Geophysical Research Letters*, **38(12)**, L12703, doi:10.1029/2011GL047436.
- Marini, L., M. Ayres, A. Battisti, and M. Faccoli, 2012:** Climate affects severity and altitudinal distribution of outbreaks in an eruptive bark beetle. *Climatic Change*, **115(2)**, 327-341.
- Markovic, D., U. Scharfenberger, S. Schmutz, F. Pletterbauer, and C. Wolter, 2013:** Variability and alterations of water temperatures across the Elbe and Danube River Basins. *Climatic Change*, **119(2)**, 375-389.
- Marlon, J.R., P.J. Bartlein, M.K. Walsh, S.P. Harrison, K.J. Brown, M.E. Edwards, P.E. Higuera, M.J. Power, R.S. Anderson, C. Briles, A. Brunelle, C. Carcaillet, M. Daniels, F.S. Hu, M. Lavoie, C. Long, T. Minckley, P.J.H. Richard, A.C. Scott, D.S. Shafer, W. Tinner, C.E. Umbanhowar, and C. Whitlock, 2009:** Wildfire responses to abrupt climate change in North America. *Proceedings of the National Academy of Sciences of the United States of America*, **106(8)**, 2519-2524.
- Marlon, J.R., P.J. Bartlein, A.-L. Daniau, S.P. Harrison, S.Y. Maezumi, M.J. Power, W. Tinner, and B. Vanni re, 2013:** Global biomass burning: a synthesis and review of Holocene paleofire records and their controls. *Quaternary Science Reviews*, **65**, 5-25.
- Marti-Roura, M., P. Casals, and J. Romany , 2011:** Temporal changes in soil organic C under Mediterranean shrublands and grasslands: impact of fire and drought. *Plant and Soil*, **338(1-2)**, 289-300.
- Martin, D., T. Lal, C.B. Sachdev, and J.P. Sharma, 2010:** Soil organic carbon storage changes with climate change, landform and land use conditions in Garhwal hills of the Indian Himalayan mountains. *Agriculture, Ecosystems & Environment*, **138(1-2)**, 64-73.
- Martin, T.E. and J.L. Maron, 2012:** Climate impacts on bird and plant communities from altered animal-plant interactions. *Nature Climate Change*, **2(3)**, 195-200.
- Martinez-Alier, J., 2011:** The EROI of Agriculture and its use by the Via Campesina. *The Journal of Peasant Studies*, **38(1)**, 145-160.
- Martinez, P.J., 2012:** Invasive crayfish in a high desert river: implications of concurrent invaders and climate change. *Aquatic Invasions*, **7(2)**, 219-234.
- Maseyk, K., D. Hemming, A. Angert, S.W. Leavitt, and D. Yakir, 2011:** Increase in water-use efficiency and underlying processes in pine forests across a precipitation gradient in the dry Mediterranean region over the past 30 years. *Oecologia*, **167(2)**, 573-585.
- Maslin, M., M. Owen, R. Betts, S. Day, T. Dunkley Jones, and A. Ridgwell, 2010:** Gas hydrates: past and future geohazard? *Philosophical Transactions of the Royal Society A*, **368(1919)**, 2369-2393.
- Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe, and F.W. Zwiers, 2010:** *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 5 pp., www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.
- Matthews, S.N., L.R. Iverson, A.M. Prasad, M.P. Peters, and P.G. Rodewald, 2011:** Modifying climate change habitat models using tree species-specific assessments of model uncertainty and life history-factors. *Forest Ecology and Management*, **262(8)**, 1460-1472.
- Matthiessen, B., E. Mielke, and U. Sommer, 2010:** Dispersal decreases diversity in heterogeneous metacommunities by enhancing regional competition. *Ecology*, **91(7)**, 2022-2033.
- Mattila, N., V. Kaitala, A. Komonen, J. Paivinen, and J.S. Kotiaho, 2011:** Ecological correlates of distribution change and range shift in butterflies. *Insect Conservation and Diversity*, **4(4)**, 239-246.
- Matusick, G., K.X. Ruthrof, and G.S.J. Hardy, 2012:** Drought and heat triggers sudden and severe dieback in a dominant Mediterranean-type woodland species. *Open Journal of Forestry*, **2(4)**, 183-186.
- Matusick, G., K.X. Ruthrof, N.C. Brouwers, B. Dell, and G.S.J. Hardy, 2013:** Sudden forest canopy collapse corresponding with extreme drought and heat in a Mediterranean-type eucalypt forest in southwestern Australia. *European Journal of Forest Research*, **132(3)**, 497-510.
- Matzek, V., 2012:** Trait values, not trait plasticity, best explain invasive species' performance in a changing environment. *PLoS One*, **7(10)**, e48821, doi:10.1371/journal.pone.0048821.
- Mayle, F.E. and M.J. Power, 2008:** Impact of a drier Early-Mid-Holocene climate upon Amazonian forests. *Philosophical Transactions of the Royal Society B*, **363(1498)**, 1829-1838.
- McAlpine, C.A., J. Syktus, J.G. Ryan, R.C. Deo, G.M. Mckean, H.A. McGowan, and S.R. Phinn, 2009:** A continent under stress: interactions, feedbacks and risks associated with impact of modified land cover on Australia's climate. *Global Change Biology*, **15(9)**, 2206-2223.

- McCain, C.M.** and R.K. Colwell, 2011: Assessing the threat to montane biodiversity from discordant shifts in temperature and precipitation in a changing climate. *Ecology Letters*, **14**(12), 1236-1245.
- McCarthy, M.P., M.J. Best,** and R.A. Betts, 2010: Climate change in cities due to global warming and urban effects. *Geophysical Research Letters*, **37**, L09705.
- McDougall, K.L., J.M. Alexander, S. Haider, A. Pauchard, N.G. Walsh,** and C. Kueffer, 2011: Alien flora of mountains: global comparisons for the development of local preventive measures against plant invasions. *Diversity and Distributions*, **17**(1), 103-111.
- McDowell, N.G., D.J. Beerling, D.D. Breshears, R.A. Fisher, K.F. Raffa,** and M. Stitt, 2011: The interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends in Ecology & Evolution*, **26**(10), 523-532.
- McGeoch, M.A., S.H.M. Butchart, D. Spear, E. Marais, E.J. Kleynhans, A. Symes, J. Chanson,** and M. Hoffmann, 2010: Global indicators of biological invasion: species numbers, biodiversity impact and policy responses. *Diversity and Distributions*, **16**(1), 95-108.
- McGuire, A.D., F.S. Chapin, C. Wirth, M. Apps, J. Bhatti, T. Callaghan, T.R. Christensen, J.S. Clein, M. Fukuda, T. Maximov, A. Onuchin, A. Shvidenko, E. Vaganov, J.G. Canadell, D.E. Pataki,** and L.F. Pitelka, 2007: Responses of high latitude ecosystems to global change: potential consequences for the climate system. In: *Terrestrial Ecosystems in a Changing World* [Canadell, J.G., D.E. Pataki, and L.F. Pitelka (eds.)]. Global Change – The IGBP Series, Springer-Verlag, Berlin, Heidelberg, Germany, pp. 297-310.
- McGuire, A.D., D.J. Hayes, D.W. Kicklighter, M. Manizza, Q. Zhuang, M. Chen, M.J. Follows, K.R. Gurney, J.W. McClelland, J.M. Melillo, B.J. Peterson, and R.G. Prinn,** 2010: An analysis of the carbon balance of the Arctic Basin from 1997 to 2006. *Tellus Series B: Chemical and Physical Meteorology*, **62**(5), 455-474.
- McGuire, A.D., T.R. Christensen, D. Hayes, A. Heroult, E. Euskirchen, Y. Yi, J.S. Kimball, C. Koven, P. Laflour, P.A. Miller, W. Oechel, P. Peylin,** and M. Williams, 2012: An assessment of the carbon balance of arctic tundra: comparisons among observations, process models, and atmospheric inversions. *Biogeosciences Discussions*, **9**(4), 4543-4594.
- McKenzie, V.J.** and A.C. Peterson, 2012: Pathogen pollution and the emergence of a deadly amphibian pathogen. *Molecular Ecology*, **21**(21), 5151-5154.
- McKinney, M.,** 2008: Effects of urbanization on species richness: a review of plants and animals. *Urban Ecosystems*, **11**(2), 161-176.
- McLachlan, J.S., J.S. Clark, and P.S. Manos,** 2005: Molecular indicators of tree migration capacity under rapid climate change. *Ecology*, **86**(8), 2088-2098.
- McLaughlin, S.B., M. Nosal, S.D. Wullschlegler,** and G. Sun, 2007: Interactive effects of ozone and climate on tree growth and water use in a southern Appalachian forest in the USA. *New Phytologist*, **174**(1), 109-124.
- McMahon, S.M., S.P. Harrison, W.S. Armbruster, P.J. Bartlein, C.M. Beale, M.E. Edwards, J. Kattge, G. Midgley, X. Morin,** and I.C. Prentice, 2011: Improving assessment and modelling of climate change impacts on global terrestrial biodiversity. *Trends in Ecology & Evolution*, **26**(5), 249-259.
- McMenamin, S.K.** and L. Hannah, 2012: First extinctions on land. In: *Saving a Million Species: Extinction Risk from Climate Change* [Hannah, L. (ed.)]. Island Press, Washington, DC, USA, pp. 89-102.
- Mehl, J.W., C.J. Geldenhuys, J. Roux,** and M.J. Wingfield, 2010: Die-back of kiasat (*Pterocarpus angolensis*) in southern Africa: a cause for concern? *Southern Forests: a Journal of Forest Science*, **72**(3-4), 121-132.
- Meier, E.S., H. Lischke, D.R. Schmatz,** and N.E. Zimmermann, 2012: Climate, competition and connectivity affect future migration and ranges of European trees. *Global Ecology and Biogeography*, **21**(2), 164-178.
- Menéndez, R., A. Gonzalez-Megias, O.T. Lewis, M.R. Shaw,** and C.D. Thomas, 2008: Escape from natural enemies during climate-driven range expansion: a case study. *Ecological Entomology*, **33**(3), 413-421.
- Menge, D.N.L.** and C.B. Field, 2007: Simulated global changes alter phosphorus demand in annual grassland. *Global Change Biology*, **13**(12), 2582-2591.
- Menzel, A., T.H. Sparks, N. Estrella, E. Koch, A. Aasa, R. Ahas, K. Alm-Kubler, P. Bissolli, O. Braslavská, A. Briede, F.M. Chmielewski, Z. Crepinsek, Y. Curnel, A. Dahl, C. Defila, A. Donnelly, Y. Filella, K. Jatcza, F. Mage, A. Mestre, O. Nordli, J. Penuelas, P. Pirinen, V. Remisova, H. Scheffinger, M. Striz, A. Susnik, A.J.H. Van Vliet, F.E. Wielgolaski, S. Zach,** and A. Züst, 2006: European phenological response to climate change matches the warming pattern. *Global Change Biology*, **12**(10), 1969-1976.
- Mercado, L.M., N. Bellouin, S. Sitoh, O. Boucher, C. Huntingford, M. Wild,** and P.M. Cox, 2009: Impact of changes in diffuse radiation on the global land carbon sink. *Nature*, **458**(7241), 1014-1017.
- Merilä, J.,** 2012: Evolution in response to climate change: in pursuit of the missing evidence. *Bioessays*, **34**(9), 811-818.
- Meyers, E.M., B. Dobrowski,** and C.L. Tague, 2010: Climate change impacts on flood frequency, intensity, and timing may affect trout species in Sagehen Creek, California. *Transactions of the American Fisheries Society*, **139**(6), 1657-1664.
- Meyfroidt, P.** and E.F. Lambin, 2011: Global forest transition: prospects for an end to deforestation. *Annual Review of Environment and Resources*, **36**, 343-371.
- Michaelian, M., E.H. Hogg, R.J. Hall,** and E. Arsenaault, 2011: Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. *Global Change Biology*, **17**(6), 2084-2094.
- Michalski, S.G., W. Durka, A. Jentsch, J. Kreyling, S. Pompe, O. Schweiger, E. Willner,** and C. Beierkuhnlein, 2010: Evidence for genetic differentiation and divergent selection in an autotetraploid forage grass (*Arrhenatherum elatius*). *TAG Theoretical and Applied Genetics*, **120**(6), 1151-1162.
- Michelutti, N., A.P. Wolfe, R.D. Vinebrooke, B. Rivard,** and J.P. Briner, 2005: Recent primary production increases in arctic lakes. *Geophysical Research Letters*, **32**(19), L19715, doi:10.1029/2005GL023693.
- Midgley, G.F., I.D. Davies, C.H. Albert, R. Altwegg, L. Hannah, G.O. Hughes, L.R. O'Halloran, C. Seo, J.H. Thorne,** and W. Thuiller, 2010: BioMove – an integrated platform simulating the dynamic response of species to environmental change. *Ecography*, **33**(3), 612-616.
- Mihoub, J.B., N.G. Mouawad, P. Pilard, F. Jiguet, M. Low,** and C. Teplitsky, 2012: Impact of temperature on the breeding performance and selection patterns in lesser kestrels *Falco naumanni*. *Journal of Avian Biology*, **43**(5), 472-480.
- Miles, L., A.C. Newton, R.S. DeFries, C. Ravillious, I. May, S. Blyth, V. Kapos,** and J.E. Gordon, 2006: A global overview of the conservation status of tropical dry forests. *Journal of Biogeography*, **33**(3), 491-505.
- Millar, C., R. Westfall, D. Delany, J. King,** and L. Graumlich, 2004: Response of subalpine conifers in the Sierra Nevada, California, U.S.A., to 20th-century warming and decadal climate variability. *Arctic, Antarctic, and Alpine Research*, **36**(2), 181-200.
- Millar, C.I., R.D. Westfall, D.L. Delany, M.J. Bokach, A.L. Flint,** and L.E. Flint, 2012: Forest mortality in high-elevation whitebark pine (*Pinus albicaulis*) forests of eastern California, USA; influence of environmental context, bark beetles, climatic water deficit, and warming. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **42**(4), 749-765.
- Millennium Ecosystem Assessment,** 2003: *Ecosystems and Human Well-being: A Framework for Assessment*. Island Press, Washington, DC, USA, 212 pp.
- Millennium Ecosystem Assessment,** 2005a: *Ecosystems and Human Well-being: Desertification Synthesis*. World Resources Institute, Washington, DC, USA, 26 pp.
- Millennium Ecosystem Assessment,** 2005b: *Ecosystems and Human Well-being: Biodiversity Synthesis*. World Resources Institute, Washington, DC, USA, 86 pp.
- Millennium Ecosystem Assessment,** 2005c: *Ecosystems and Human Well-being: Current State and Trends, Vol. 1*. Island Press, Washington, DC, USA, 917 pp.
- Millennium Ecosystem Assessment,** 2005d: *Ecosystems and Human Well-being: Scenarios, Vol. 2*. Island Press, Washington, DC, USA, 560 pp.
- Millennium Ecosystem Assessment,** 2005e: *Ecosystems and Human Well-being: Policy Responses, Vol. 3*. Island Press, Washington, DC, USA, 621 pp.
- Miller-Rushing, A.J., T.L. Lloyd-Evans, R.B. Primack,** and P. Satzinger, 2008: Bird migration times, climate change, and changing population sizes. *Global Change Biology*, **14**(9), 1959-1972.
- Mills, G., F. Hayes, S. Wilkinson,** and W.J. Davies, 2009: Chronic exposure to increasing background ozone impairs stomatal functioning in grassland species. *Global Change Biology*, **15**(6), 1522-1533.
- Mills, G., F. Hayes, D. Simpson, L. Emberson, D. Norris, H. Harmens,** and P. Buker, 2011: Evidence of widespread effects of ozone on crops and (semi-)natural vegetation in Europe (1990-2006) in relation to AOT40-and flux-based risk maps. *Global Change Biology*, **17**(1), 592-613.
- Minnich, R.A.,** 2007: Southern California conifer forests. In: *Terrestrial Vegetation of California* [Barbour, M., T. Keeler-Wolf, and A. A. Schoenherr (eds.)]. University of California Press, Berkeley, CA, USA, pp. 502-538.
- Minteer, B.A.** and J.P. Collins, 2010: Move it or lose it? The ecological ethics of relocating species under climate change. *Ecological Applications*, **20**(7), 1801-1804.
- Miranda, J.D., F.M. Padilla,** and F.I. Pugnaire, 2009: Response of a Mediterranean semiarid community to changing patterns of water supply. *Perspectives in Plant Ecology Evolution and Systematics*, **11**(4), 255-266.

- Mishra, V., K.A. Cherkauer, D. Niyogi, M. Lei, B.C. Pijanowski, D.K. Ray, L.C. Bowling, and G. Yang, 2010: A regional scale assessment of land use/land cover and climatic changes on water and energy cycle in the upper Midwest United States. *International Journal of Climatology*, **30**(13), 2025-2044.
- Mitas, C.M. and A. Clement, 2005: Has the Hadley cell been strengthening in recent decades? *Geophysical Research Letters*, **32**(3), L030809, doi:10.1029/2004GL021765.
- Mitchard, E.T.A., S.S. Saatchi, F.F. Gerard, S.L. Lewis, and P. Meir, 2009: Measuring woody encroachment along a forest-savanna boundary in Central Africa. *Earth Interactions*, **13**(8), 1-29.
- Mitchell, T.D. and P.D. Jones, 2005: An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology*, **25**(6), 693-712.
- Miyake, S., M. Renouf, A. Peterson, C. McAlpine, and C. Smith, 2012: Land-use and environmental pressures resulting from current and future bioenergy crop expansion: a review. *Journal of Rural Studies*, **28**(4), 650-658.
- Mohan, J.E., L.H. Ziska, W.H. Schlesinger, R.B. Thomas, R.C. Sicher, K. George, and J.S. Clark, 2006: Biomass and toxicity responses of poison ivy (*Toxicodendron radicans*) to elevated atmospheric CO₂. *Proceedings of the National Academy of Sciences of the United States of America*, **103**(24), 9086-9089.
- Moiseyev, A., B. Solberg, A.M.I. Kallio, and M. Lindner, 2011: An economic analysis of the potential contribution of forest biomass to the EU RES target and its implications for the EU forest industries. *Journal of Forest Economics*, **17**(2), 197-213.
- Molelele, N.M., S. Ringrose, W. Matheson, and C. Vanderpost, 2002: More woody plants? The status of bush encroachment in Botswana's grazing areas. *Journal of Environmental Management*, **64**(1), 3-11.
- Møller, A.P., D. Rubolini, and E. Lehikoinen, 2008: Populations of migratory bird species that did not show a phenological response to climate change are declining. *Proceedings of the National Academy of Sciences of the United States of America*, **105**(42), 16195-16200.
- Monahan, W.B. and M.W. Tingley, 2012: Niche tracking and rapid establishment of distributional equilibrium in the house sparrow show potential responsiveness of species to climate change. *PLoS One*, **7**(7), e42097, doi:10.1371/journal.pone.0042097.
- Monteith, D.T., J.L. Stoddard, C.D. Evans, H.A. de Wit, M. Forsius, T. Hogasen, A. Wilander, B.L. Skjelkvale, D.S. Jeffries, J. Vuorenmaa, B. Keller, J. Kopacek, and J. Vesely, 2007: Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. *Nature*, **450**(7169), 537-540.
- Montoya, J.M. and D. Raffaelli, 2010: Climate change, biotic interactions and ecosystem services. *Philosophical Transactions of the Royal Society B*, **365**(1549), 2013-2018.
- Mooney, H.A., S.H. Bullock, and E. Medina, 1995: Introduction. In: *Seasonally Dry Tropical Forests* [Bullock, S.H., H.A. Mooney, and E. Medina (eds.)]. Cambridge University Press, Cambridge, UK, pp. 1-8.
- Moore, S., C.D. Evans, S.E. Page, M.H. Garnett, T.G. Jones, C. Freeman, A. Hooijer, A.J. Wiltshire, S.H. Limin, and V. Gauci, 2013: Deep instability of deforested tropical peatlands revealed by fluvial organic carbon fluxes. *Nature*, **493**(7434), 660-663.
- Morecroft, M.D., H.Q.P. Crick, S.J. Duffield, and N.A. Macgregor, 2012: Resilience to climate change: translating principles into practice. *Journal of Applied Ecology*, **49**(3), 547-551.
- Morin, X. and W. Thuiller, 2009: Comparing niche- and process-based models to reduce prediction uncertainty in species range shifts under climate change. *Ecology*, **90**(5), 1301-1313.
- Morin, X., C. Augspurger, and I. Chuine, 2007: Process-based modeling of species' distributions: what limits temperate tree species' range boundaries? *Ecology*, **88**(9), 2280-2291.
- Moritz, C. and R. Agudo, 2013: The future of species under climate change: resilience or decline? *Science*, **341**(6145), 504-508.
- Moritz, M.A., M.A. Parisien, E. Batllori, M.A. Krawchuk, J. Van Dorn, D.J. Ganz, and K. Hayhoe, 2012: Climate change and disruptions to global fire activity. *Gcosphere*, **3**(6), 49, doi:10.1890/ES11-00345.
- Morrison, J., M.C. Quick, and M.G.G. Foreman, 2002: Climate change in the Fraser River watershed: flow and temperature projections. *Journal of Hydrology*, **263**(1-4), 230-244.
- Mueller, A.D., G.A. Islebe, M.B. Hillesheim, D.A. Grzesik, F.S. Anselmetti, D. Ariztegui, M. Brenner, J.H. Curtis, D.A. Hodell, and K.A. Venz, 2009: Climate drying and associated forest decline in the lowlands of northern Guatemala during the late Holocene. *Quaternary Research*, **71**(2), 133-141.
- Mueller, D.R., P. Van Hove, D. Antoniadis, M.O. Jeffries, and W.F. Vincent, 2009: High Arctic lakes as sentinel ecosystems: cascading regime shifts in climate, ice cover, and mixing. *Limnology and Oceanography*, **54**(6), 2371-2385.
- Mueller, R.C., C.M. Scudder, M.E. Porter, R.T. Trotter, C.A. Gehring, and T.G. Whitham, 2005: Differential tree mortality in response to severe drought: evidence for long-term vegetation shifts. *Journal of Ecology*, **93**(6), 1085-1093.
- Muhlfeld, C.C., J.J. Giersch, F.R. Hauer, G.T. Pederson, G. Luikart, D.P. Peterson, C.C. Downs, and D.B. Fagre, 2011: Climate change links fate of glaciers and an endemic alpine invertebrate. *Climatic Change*, **106**(2), 337-345.
- Muñoz-Robles, C., N. Reid, M. Tighe, S.V. Briggs, and B. Wilson, 2011: Soil hydrological and erosional responses in areas of woody encroachment, pasture and woodland in semi-arid Australia. *Journal of Arid Environments*, **75**(10), 936-945.
- Murdiyoso, D., K. Hergoualc'h, and L.V. Verchot, 2010: Opportunities for reducing greenhouse gas emissions in tropical peatlands. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(46), 19655-19660.
- Musolin, D.L., D. Tougou, and K. Fujisaki, 2010: Too hot to handle? Phenological and life-history responses to simulated climate change of the southern green stink bug *Nezara viridula* (Heteroptera: Pentatomidae). *Global Change Biology*, **16**(1), 73-87.
- Myers-Smith, I.H., B.C. Forbes, M. Wilmking, M. Hallinger, T. Lantz, D. Blok, K.D. Tape, M. Macias-Fauria, U. Sass-Klaassen, E. Levesque, S. Boudreau, P. Ropars, L. Hermanutz, A. Trant, L.S. Collier, S. Weijers, J. Rozema, S.A. Rayback, N.M. Schmidt, G. Schaepman-Strub, S. Wipf, C. Rixen, C.B. Menard, S. Venn, S. Goetz, L. Andreu-Hayles, S. Elmendorf, V. Ravolainen, J. Welker, P. Grogan, H.E. Epstein, and D.S. Hik, 2011: Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. *Environmental Research Letters*, **6**(4), 045509, doi:10.1088/1748-9326/6/4/045509.
- Nabuurs, G.J., G.M. Hengeveld, D.C. van der Werf, and A.H. Heidema, 2010: European forest carbon balance assessed with inventory based methods – an introduction to a special section. *Forest Ecology and Management*, **260**(3), 239-240.
- Naito, A.T. and D.M. Cairns, 2011: Patterns and processes of global shrub expansion. *Progress in Physical Geography*, **35**(4), 423-442.
- Nakazawa, T. and H. Doi, 2012: A perspective on match/mismatch of phenology in community contexts. *Oikos*, **121**(4), 489-495.
- Nathan, R., 2006: Long-distance dispersal of plants. *Science*, **313**(5788), 786-788.
- Nathan, R., N. Horvitz, Y.P. He, A. Kuparinen, F.M. Schurr, and G.G. Katul, 2011: Spread of North American wind-dispersed trees in future environments. *Ecology Letters*, **14**(3), 211-219.
- Nemet, G.F., 2009: Net radiative forcing from widespread deployment of photovoltaics. *Environmental Science and Technology*, **43**(6), 2173-2178.
- Nepstad, D.C., I.M. Tohver, D. Ray, P. Moutinho, and G. Cardinot, 2007: Mortality of large trees and lianas following experimental drought in an Amazon forest. *Ecology*, **88**(9), 2259-2269.
- Nepstad, D.C., C.M. Stickler, B. Soares, and F. Merry, 2008: Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. *Philosophical Transactions of the Royal Society B*, **363**(1498), 1737-1746.
- Nepstad, D.C., B.S. Soares, F. Merry, A. Lima, P. Moutinho, J. Carter, M. Bowman, A. Cattaneo, H. Rodrigues, S. Schwartzman, D.G. McGrath, C.M. Stickler, R. Lubowski, P. Piris-Cabezas, S. Rivero, A. Alencar, O. Almeida, and O. Stella, 2009: The end of deforestation in the Brazilian Amazon. *Science*, **326**(5958), 1350-1351.
- Nepstad, D.C., W. Boyd, C.M. Stickler, T. Bezerra, and A.A. Azevedo, 2013: Responding to climate change and the global land crisis: REDD+, market transformation and low-emissions rural development. *Philosophical Transactions of the Royal Society B*, **368**(1619), 20120167, doi:10.1098/rstb.2012.0167.
- Ni, J., 2011: Impacts of climate change on Chinese ecosystems: key vulnerable regions and potential thresholds. *Regional Environmental Change*, **11**, S49-S64.
- Niboyet, A., J.R. Brown, P. Dijkstra, J.C. Blankinship, P.W. Leadley, X. Le Roux, L. Barthes, R.L. Barnard, C.B. Field, and B.A. Hungate, 2011: Global change could amplify fire effects on soil greenhouse gas emissions. *PLoS One*, **6**(6), e20105, doi:10.1371/journal.pone.0020105.
- Nicholls, R.J., 2004: Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. *Global Environmental Change: Human and Policy Dimensions*, **14**(1), 69-86.
- Nielsen, U.N. and D.H. Wall, 2013: The future of soil invertebrate communities in polar regions: different climate change responses in the Arctic and Antarctic? *Ecology Letters*, **16**(3), 409-419.
- Nilsson, C., C.A. Reidy, M. Dynesius, and C. Revenga, 2005: Fragmentation and flow regulation of the world's large river systems. *Science*, **308**(5720), 405-408.

- Nock, C.A., P.J. Baker, W. Wanek, A. Leis, M. Grabner, S. Bunyavejchewin, and P. Hietz, 2011: Long-term increases in intrinsic water-use efficiency do not lead to increased stem growth in a tropical monsoon forest in western Thailand. *Global Change Biology*, **17**(2), 1049-1063.
- Nogues-Bravo, D., R. Ohlemuller, P. Batra, and M.B. Araujo, 2010: Climate predictors of Late Quaternary extinctions. *Evolution*, **64**(8), 2442-2449.
- Norberg, J., M.C. Urban, M. Vellend, C.A. Klausmeier, and N. Loeuille, 2012: Evolutionary responses of biodiversity to climate change. *Nature Climate Change*, **2**(10), 747-751.
- Norby, R.J. and D.R. Zak, 2011: Ecological lessons from free-air CO₂ enrichment (FACE) experiments. *Annual Review of Ecology, Evolution, and Systematics*, **42**, 181-203.
- Normand, S., U.A. Treier, C. Randin, P. Vittoz, A. Guisan, and J.C. Svenning, 2009: Importance of abiotic stress as a range-limit determinant for European plants: insights from species responses to climatic gradients. *Global Ecology and Biogeography*, **18**(4), 437-449.
- Nowicki, P., A. Pepkowska, J. Kudlek, P. Skorka, M. Witek, J. Settele, and M. Woyciechowski, 2007: From metapopulation theory to conservation recommendations: lessons from spatial occurrence and abundance patterns of Maculinea butterflies. *Biological Conservation*, **140**(1-2), 119-129.
- O'Connor, F.M., O. Boucher, N. Gedney, C.D. Jones, G.A. Folberth, R. Coppel, P. Friedlingstein, W.J. Collins, J. Chappellaz, J. Ridley, and C.E. Johnson, 2010: Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: a review. *Reviews of Geophysics*, **48**(4), RG4005, doi:10.1029/2010RG000326.
- O'Donnell, J.A., J.W. Harden, A.D. McGuire, M.Z. Kanevskiy, M.T. Jorgenson, and X.M. Xu, 2011: The effect of fire and permafrost interactions on soil carbon accumulation in an upland black spruce ecosystem of interior Alaska: implications for post-thaw carbon loss. *Global Change Biology*, **17**(3), 1461-1474.
- O'Halloran, T.L., B.E. Law, M.L. Goulden, Z. Wang, J.G. Barr, C. Schaaf, M. Brown, J.D. Fuentes, M. Gökede, A. Black, and V. Engel, 2012: Radiative forcing of natural forest disturbances. *Global Change Biology*, **18**(2), 555-565.
- O'Reilly, C.M., S.R. Alin, P.D. Plisnier, A.S. Cohen, and B.A. McKee, 2003: Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature*, **424**(6950), 766-768.
- Obersteiner, M., H. Böttcher, and Y. Yamagata, 2010: Terrestrial ecosystem management for climate change mitigation. *Current Opinion in Environmental Sustainability*, **2**(4), 271-276.
- OECD and FAO, 2010: *OECD-FAO Agricultural Outlook 2010-2019*. Organisation for Economic Co-operation and Development (OECD) and the Food and Agriculture Organization of the United Nations (FAO), OECD Publishing, Paris, France, 247 pp.
- Ogawa-Onishi, Y., P.M. Berry, and N. Tanaka, 2010: Assessing the potential impacts of climate change and their conservation implications in Japan: a case study of conifers. *Biological Conservation*, **143**(7), 1728-1736.
- Oleszczuk, R., K. Regina, L. Szajdak, H. Höper, and V. Maryganova, 2008: Impacts of agricultural utilization of peat soils on the greenhouse gas balance. In: *Peatlands and Climate Change* [Strack, M. (ed.)]. International Peat Society, Jyväskylä, Finland, pp. 70-97.
- Oliver, R.J., J.W. Finch, and G. Taylor, 2009: Second generation bioenergy crops and climate change: a review of the effects of elevated atmospheric CO₂ and drought on water use and the implications for yield. *Global Change Biology Bioenergy*, **1**(2), 97-114.
- Oliver, T., J.K. Hill, C.D. Thomas, T. Brereton, and D.B. Roy, 2009: Changes in habitat specificity of species at their climatic range boundaries. *Ecology Letters*, **12**(10), 1091-1102.
- Oliver, T.H., S. Gillings, M. Girardello, G. Rapacciuolo, T.M. Brereton, G.M. Siriwardena, D.B. Roy, R. Pywell, and R.J. Fuller, 2012a: Population density but not stability can be predicted from species distribution models. *Journal of Applied Ecology*, **49**(3), 581-590.
- Oliver, T.H., R.J. Smithers, S. Bailey, C.A. Walmsley, and K. Watts, 2012b: A decision framework for considering climate change adaptation in biodiversity conservation planning. *Journal of Applied Ecology*, **49**(6), 1247-1255.
- Oltmans, S.J., A.S. Lefohn, J.M. Harris, D.W. Tarasick, A.M. Thompson, H. Wernli, B.J. Johnson, P.C. Novelli, S.A. Montzka, J.D. Ray, L.C. Patrick, C. Sweeney, A. Jefferson, T. Dann, and J. Davies, 2006: Long term changes in tropospheric ozone. *Atmospheric Environment*, **40**(17), 3156-3173.
- Ooi, M.K.J., T.D. Auld, and A.J. Denham, 2009: Climate change and bet-hedging: interactions between increased soil temperatures and seed bank persistence. *Global Change Biology*, **15**(10), 2375-2386.
- Ormerod, S.J., 2009: Climate change, river conservation and the adaptation challenge. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **19**(6), 609-613.
- Osawa, A., O.A. Zyryanova, Y. Matsuura, T. Kajimoto, and R.W. Wein, 2010: *Permafrost Ecosystems: Siberian Larch Forests*. Springer, New York, NY, USA, 502 pp.
- Ozgul, A., D.Z. Childs, M.K. Oli, K.B. Armitage, D.T. Blumstein, L.E. Olson, S. Tuljapurkar, and T. Coulson, 2010: Coupled dynamics of body mass and population growth in response to environmental change. *Nature*, **466**(7305), 482-485.
- Pacifici, M., L. Santini, M. Di Marco, D. Baisero, L. Francucci, G. Grottole Marassini, P. Visconti, and C. Rondinini, 2013: Generation lengths for mammals. *Nature Conservation*, **5**(2013), 89-94, doi:10.3897/natureconservation.5.5734.
- Paerl, H.W., N.S. Hall, and E.S. Calandrino, 2011: Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. *Science of the Total Environment*, **409**(10), 1739-1745.
- Page, S.E., F. Siebert, J.O. Rieley, H.D. Boehm, A. Jaya, and S. Limin, 2002: The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, **420**(6911), 61-65.
- Page, S.E., J.O. Rieley, and C.J. Banks, 2011: Global and regional importance of the tropical peatland carbon pool. *Global Change Biology*, **17**(2), 798-818.
- Pan, Y., R. Birdsey, J. Hom, and K. McCullough, 2009: Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of US Mid-Atlantic temperate forests. *Forest Ecology and Management*, **259**(2), 151-164.
- Pan, Y., R. Birdsey, J. Fang, R. Houghton, P. Kauppi, W.A. Kurz, O.L. Phillips, A. Shvidenko, S.L. Lewis, J.G. Canadell, P. Ciais, R.B. Jackson, S. Pacala, A.D. McGuire, S. Piao, A. Rautiainen, S. Sitch, and D. Hayes, 2011: A large and persistent carbon sink in the world's forests. *Science*, **333**(6045), 988-993.
- Parent, M.B. and D. Verbyla, 2010: The browning of Alaska's boreal forest. *Remote Sensing*, **2**(12), 2729-2747.
- Parker-Allie, F., C.F. Musil, and W. Thuiller, 2009: Effects of climate warming on the distributions of invasive Eurasian annual grasses: a South African perspective. *Climatic Change*, **94**(1-2), 87-103.
- Parker, B.R., R.D. Vinebrooke, and D.W. Schindler, 2008: Recent climate extremes alter alpine lake ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, **105**(35), 12927-12931.
- Parmesan, C., 2006: Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology Evolution and Systematics*, **37**, 637-669.
- Parmesan, C., 2007: Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Global Change Biology*, **13**(9), 1860-1872.
- Parmesan, C. and G. Yohe, 2003: A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, **421**(6918), 37-42.
- Pataki, D.E., M.M. Carreiro, J. Cherrier, N.E. Grulke, V. Jennings, S. Pincetl, R.V. Pouyat, T.H. Whitlow, and W.C. Zipperer, 2011: Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. *Frontiers in Ecology and the Environment*, **9**(1), 27-36.
- Pateman, R.M., J.K. Hill, D.B. Roy, R. Fox, and C.D. Thomas, 2012: Temperature-dependent alterations in host use drive rapid range expansion in a butterfly. *Science*, **336**(6084), 1028-1030.
- Paterson, J.S., M.B. Araujo, P.M. Berry, J.M. Piper, and M.D.A. Rounsevell, 2008: Mitigation, adaptation, and the threat to biodiversity. *Conservation Biology*, **22**(5), 1352-1355.
- Pauli, H., M. Gottfried, K. Reiter, C. Klettner, and G. Grabherr, 2007: Signals of range expansions and contractions of vascular plants in the high Alps: observations (1994-2004) at the GLORIA master site Schrankogel, Tyrol, Austria. *Global Change Biology*, **13**, 147-156.
- Pauli, H., M. Gottfried, S. Dullinger, O. Abdaladze, M. Akhalkatsi, J.L.B. Alonso, G. Coldea, J. Dick, B. Erschbamer, R.F. Calzado, D. Ghosn, J.I. Holten, R. Kanka, G. Kazakis, J. Kollar, P. Larsson, P. Moiseev, D. Moiseev, U. Molau, J.M. Mesa, L. Nagy, G. Pelino, M. Puscas, G. Rossi, A. Stanisci, A.O. Syverhuset, J.P. Theurillat, M. Tomaselli, P. Unterluggauer, L. Villar, P. Vittoz, and G. Grabherr, 2012: Recent plant diversity changes on Europe's mountain summits. *Science*, **336**(6079), 353-355.
- Pauls, S.U., C. Nowak, M. Bálint, and M. Pfenninger, 2013: The impact of global climate change on genetic diversity within populations and species. *Molecular Ecology*, **22**(4), 925-946.
- Paun, O., R.M. Bateman, M.F. Fay, M. Hedren, L. Civeyrel, and M.W. Chase, 2010: Stable epigenetic effects impact adaptation in allopolyploid Orchids (*Dactylorhiza*: Orchidaceae). *Molecular Biology and Evolution*, **27**(11), 2465-2473.
- Payette, S., 2007: Contrasted dynamics of northern Labrador tree lines caused by climate change and migrational lag. *Ecology*, **88**(3), 770-780.

- Payette, S. and L. Filion, 1985: White spruce expansion at the tree line and recent climatic change. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **15**(1), 241-251.
- Pearce-Higgins, J.W., L. Stephen, A. Douse, and R.H.W. Langston, 2012: Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis. *Journal of Applied Ecology*, **49**(2), 386-394.
- Pearlstone, L.G., E.V. Pearlstone, and N.G. Aumen, 2010: A review of the ecological consequences and management implications of climate change for the Everglades. *Journal of the North American Benthological Society*, **29**(4), 1510-1526.
- Pearman, P.B., C.F. Randin, O. Broennimann, P. Vittoz, W.O. van der Knaap, R. Engler, G. Le Lay, N.E. Zimmermann, and A. Guisan, 2008: Prediction of plant species distributions across six millennia. *Ecology Letters*, **11**(4), 357-369.
- Pearson, R.G., 2006: Climate change and the migration capacity of species. *Trends in Ecology & Evolution*, **21**(3), 111-113.
- Pearson, R.G., 2011: *Driven to Extinction: The Impact of Climate Change on Biodiversity*. Sterling, New York, NY, USA, 263 pp.
- Pearson, R.G. and T.P. Dawson, 2003: Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography*, **12**(5), 361-371.
- Pearson, R.G., S.J. Phillips, M.M. Loranty, P.S.A. Beck, T. Damoulas, S.J. Knight, and S.J. Goetz, 2013: Shifts in Arctic vegetation and associated feedbacks under climate change. *Nature Climate Change*, **3**, 673-677.
- Pechony, O. and D.T. Shindell, 2010: Driving forces of global wildfires over the past millennium and the forthcoming century. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(45), 19167-19170.
- Pederson, G.T., L.J. Graumlich, D.B. Fagre, T. Kipfer, and C.C. Muhlfeld, 2010: A century of climate and ecosystem change in Western Montana: what do temperature trends portend? *Climatic Change*, **98**(1-2), 133-154.
- Pedlar, J.H., D.W. McKenney, I. Aubin, T. Beardmore, J. Beaulieu, L. Iverson, G.A. O'Neill, R.S. Winder, and C. Ste-Marie, 2012: Placing forestry in the assisted migration debate. *BioScience*, **62**(9), 835-842.
- Peltzer, D.A., R.B. Allen, G.M. Lovett, D. Whitehead, and D.A. Wardle, 2010: Effects of biological invasions on forest carbon sequestration. *Global Change Biology*, **16**(2), 732-746.
- Peng, C., X. Zhou, S. Zhao, X. Wang, B. Zhu, S. Piao, and J. Fang, 2009: Quantifying the response of forest carbon balance to future climate change in NE China: model validation and prediction. *Global and Planetary Change*, **66**(3-4), 179-194.
- Peng, C., Z. Ma, X. Lei, Q. Zhu, H. Chen, W. Wang, S. Liu, W. Li, X. Fang, and X. Zhou, 2011: A drought-induced pervasive increase in tree mortality across Canada's boreal forests. *Nature Climate Change*, **1**(9), 467-471.
- Peng, J., W. Dong, Y. Wenping, Y. Zhang, and J. Li, 2013: Effects of increased CO₂ on land water balance from 1850 to 1989. *Theoretical and Applied Climatology*, **111**(3-4), 483-495.
- Peñuelas, J. and M. Boada, 2003: A global change-induced biome shift in the Montseny mountains (NE Spain). *Global Change Biology*, **9**(2), 131-140.
- Peñuelas, J., C. Gordon, L. Llorens, T. Nielsen, A. Tietema, C. Beier, P. Bruna, B. Emmett, M. Estiarte, and A. Gorissen, 2004: Noninvasive field experiments show different plant responses to warming and drought among sites, seasons, and species in a north-south European gradient. *Ecosystems*, **7**(6), 598-612.
- Peñuelas, J., P. Prieto, C. Beier, C. Cesaraccio, P. de Angelis, G. de Dato, B.A. Emmett, M. Estiarte, J. Garadnai, A. Gorissen, E.K. Lang, G. Kroel-Dulay, L. Llorens, G. Pellizzaro, T. Riis-Nielsen, I.K. Schmidt, C. Circa, A. Sowerby, D. Spano, and A. Tietema, 2007: Response of plant species richness and primary productivity in shrublands along a north-south gradient in Europe to seven years of experimental warming and drought: reductions in primary productivity in the heat and drought year of 2003. *Global Change Biology*, **13**(12), 2563-2581.
- Peñuelas, J., J.G. Canadell, and R. Ogaya, 2011: Increased water-use efficiency during the 20th century did not translate into enhanced tree growth. *Global Ecology and Biogeography*, **20**(4), 597-608.
- Peñuelas, J., J. Sardans, A. Rivas-Ubach, and I.A. Janssens, 2012: The human-induced imbalance between C, N and P in Earth's life system. *Global Change Biology*, **18**(1), 3-6.
- Peñuelas, J., J. Sardans, M. Estiarte, R. Ogaya, J. Carnicer, M. Coll, A. Barbeta, A. Rivas-Ubach, J. Llusia, M. Garbulsky, I. Filella, and A.S. Jump, 2013: Evidence of current impact of climate change on life: a walk from genes to the biosphere. *Global Change Biology*, **19**(8), 2303-2338.
- Pereira, H.M., P.W. Leadley, V. Proenca, R. Alkemade, J.P.W. Scharlemann, J.F. Fernandez-Manjarres, M.B. Araujo, P. Balvanera, R. Biggs, W.W.L. Cheung, L. Chini, H.D. Cooper, E.L. Gilman, S. Guenette, G.C. Hurtt, H.P. Huntington, G.M. Mace, T. Oberdorff, C. Revenga, P. Rodrigues, R.J. Scholes, U.R. Sumaila, and M. Walpole, 2010: Scenarios for global biodiversity in the 21st century. *Science*, **330**(6010), 1496-1501.
- Péron, G., J.E. Hines, J.D. Nichols, W.L. Kendall, K.A. Peters, and D.S. Mizrahi, 2013: Estimation of bird and bat mortality at wind-power farms with superpopulation models. *Journal of Applied Ecology*, **50**(4), 902-911.
- Perry, L.G., D.C. Andersen, L.V. Reynolds, S.M. Nelson, and P.B. Shafroth, 2012: Vulnerability of riparian ecosystems to elevated CO₂ and climate change in arid and semiarid western North America. *Global Change Biology*, **18**(3), 821-842.
- Peterken, G.F. and E.P. Mountford, 1996: Effects of drought on beech in Lady Park Wood, an unmanaged mixed deciduous woodland. *Forestry*, **69**(2), 125-136.
- Peters, D.P.C., J.E. Herrick, H.C. Monger, and H.T. Huang, 2010: Soil-vegetation-climate interactions in arid landscapes: effects of the North American monsoon on grass recruitment. *Journal of Arid Environments*, **74**(5), 618-623.
- Peterson, M.A. and R.F. Denno, 1998: The influence of dispersal and diet breadth on patterns of genetic isolation by distance in phytophagous insects. *American Naturalist*, **152**(3), 428-446.
- Peterson, A.T., A. Stewart, K.I. Mohamed, and M.B. Araujo, 2008: Shifting global invasive potential of European plants with climate change. *PLoS One*, **3**(6), e2441, doi:10.1371/journal.pone.0002441.
- Peterson, A.T.S., J., R.G. Pearson, R.P. Anderson, E. Martinez-Meyer, M. Nakamura, and M.B. Araújo, 2011: *Ecological Niches and Geographic Distributions*. Princeton University Press, Princeton, NJ, USA, 328 pp.
- Petit, B. and F. Montagnini, 2006: Growth in pure and mixed plantations of tree species used in reforesting rural areas of the humid region of Costa Rica, Central America. *Forest Ecology and Management*, **233**(2-3), 338-343.
- Petitpierre, B., C. Kueffer, O. Broennimann, C. Randin, C. Daehler, and A. Guisan, 2012: Climatic niche shifts are rare among terrestrial plant invaders. *Science*, **335**(6074), 1344-1348.
- Peylin, P., P. Bousquet, C. Le Quere, P. Friedlingstein, G. McKinley, N. Gruber, P. Rayner, and P. Ciais, 2005: Multiple constraints on regional CO₂ flux variations over land and oceans. *Global Biogeochemical Cycles*, **19**(1), GB1011, doi:10.1029/2003GB002214.
- Phillimore, A.B., J.D. Hadfield, O.R. Jones, and R.J. Smithers, 2010: Differences in spawning date between populations of common frog reveal local adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(18), 8292-8297.
- Phillips, O.L., R.V. Martinez, L. Arroyo, T.R. Baker, T. Killeen, S.L. Lewis, Y. Malhi, A.M. Mendoza, D. Neill, P.N. Vargas, M. Alexiades, C. Ceron, A. Di Fiore, T. Erwin, A. Jardim, W. Palacios, M. Saldias, and B. Vinceti, 2002: Increasing dominance of large lianas in Amazonian forests. *Nature*, **418**(6899), 770-774.
- Phillips, O.L., R. Vásquez Martínez, A. Monteagudo Mendoza, T. Baker, and P. Núñez-Vargas, 2005: Large lianas as hyperdynamic elements of the tropical forest canopy. *Ecology*, **86**(5), 1250-1258.
- Phillips, O.L., L. Aragao, S.L. Lewis, J.B. Fisher, J. Lloyd, G. Lopez-Gonzalez, Y. Malhi, A. Monteagudo, J. Peacock, C.A. Quesada, G. van der Heijden, S. Almeida, I. Amaral, L. Arroyo, G. Aymard, T.R. Baker, O. Banki, L. Blanc, D. Bonal, P. Brando, J. Chave, A.C.A. de Oliveira, N.D. Cardozo, C.I. Czimczik, T.R. Feldpausch, M.A. Freitas, E. Gloor, N. Higuchi, E. Jimenez, G. Lloyd, P. Meir, C. Mendoza, A. Morel, D.A. Neill, D. Nepstad, S. Patino, M.C. Penuela, A. Prieto, F. Ramirez, M. Schwarz, J. Silva, M. Silveira, A.S. Thomas, H. ter Steege, J. Stropp, R. Vasquez, P. Zelazowski, E.A. Davila, S. Andelman, A. Andrade, K.J. Chao, T. Erwin, A. Di Fiore, E. Honorio, H. Keeling, T.J. Killeen, W.F. Laurance, A.P. Cruz, N.C.A. Pitman, P.N. Vargas, H. Ramirez-Angulo, A. Rudas, R. Salamao, N. Silva, J. Terborgh, and A. Torres-Lezama, 2009: Drought sensitivity of the Amazon rainforest. *Science*, **323**(5919), 1344-1347.
- Phillips, O.L., G. van der Heijden, S.L. Lewis, G. Lopez-Gonzalez, L.E.O.C. Aragao, J. Lloyd, Y. Malhi, A. Monteagudo, S. Almeida, E. Alvarez Davila, I. Amaral, S. Andelman, A. Andrade, L. Arroyo, G. Aymard, T.R. Baker, L. Blanc, D. Bonal, A.C. Alves de Oliveira, K.-J. Chao, N. Davila Cardozo, L. da Costa, T.R. Feldpausch, J.B. Fisher, N.M. Fyllas, M.A. Freitas, D. Galbraith, E. Gloor, N. Higuchi, E. Honorio, E. Jimenez, H. Keeling, T.J. Killeen, J.C. Lovett, P. Meir, C. Mendoza, A. Morel, P. Nunez Vargas, S. Patino, K.S.H. Peh, A. Pena Cruz, A. Prieto, C.A. Quesada, F. Ramirez, H. Ramirez, A. Rudas, R. Salamao, M. Schwarz, J. Silva, M. Silveira, J.W.F. Slik, B. Sonke, A.S. Thomas, J. Stropp, J.R.D. Taplin, R. Vasquez, and E. Vilanova, 2010: Drought-mortality relationships for tropical forests. *New Phytologist*, **187**(3), 631-646.

- Pielke**, R.A., A. Pitman, D. Niyogi, R. Mahmood, C. McAlpine, F. Hossain, K.K. Goldewijk, U. Nair, R. Betts, S. Fall, M. Reichstein, P. Kabat, and N. de Noblet, 2011: Land use/land cover changes and climate: modeling analysis and observational evidence. *Wiley Interdisciplinary Reviews: Climate Change*, **2(6)**, 828-850.
- Pitman**, A.J., G.T. Narisma, and J. McAneney, 2007: The impact of climate change on the risk of forest and grassland fires in Australia. *Climatic Change*, **84(3-4)**, 383-401.
- Pitman**, A.J., N. de Noblet-Ducoudre, F.T. Cruz, E.L. Davin, G.B. Bonan, V. Brovkin, M. Claussen, C. Delire, L. Ganzeveld, V. Gayler, B.J.J.M. van den Hurk, P.J. Lawrence, M.K. van der Molen, C. Muller, C.H. Reick, S.I. Seneviratne, B.J. Strengers, and A. Voldoire, 2009: Uncertainties in climate responses to past land cover change: first results from the LUCID intercomparison study. *Geophysical Research Letters*, **36(14)**, L14814, doi:10.1029/2009GL039076.
- Plevin**, R.J., M. O'Hare, A.D. Jones, M.S. Torn, and H.K. Gibbs, 2010: Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated. *Environmental Science & Technology*, **44(21)**, 8015-8021.
- Poff**, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M.C. Freeman, J. Henriksen, R.B. Jacobson, J.G. Kennen, D.M. Merritt, J.H. O'Keefe, J.D. Olden, K. Rogers, R.E. Tharme, and A. Warner, 2010: The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology*, **55(1)**, 147-170.
- Polis**, G.A., W.B. Anderson, and R.D. Holt, 1997: Toward an integration of landscape and food web ecology: the dynamics of spatially subsidized food webs. *Annual Review of Ecology and Systematics*, **28**, 289-316.
- Ponniiah**, M. and J.M. Hughes, 2004: The evolution of Queensland spiny mountain crayfish of the genus *Euastacus*. I. Testing vicariance and dispersal with interspecific mitochondrial DNA. *Evolution*, **58(5)**, 1073-1085.
- Porter**, T.J. and M.F.J. Pisaric, 2011: Temperature-growth divergence in white spruce forests of Old Crow Flats, Yukon Territory, and adjacent regions of northwestern North America. *Global Change Biology*, **17(11)**, 3418-3430.
- Post**, E. and J. Brodie, 2012: Extinction risk at high latitudes. In: *Saving a Million Species: Extinction Risk From Climate Change* [Hannah, L. (ed.)]. Island Press, Washington, DC, USA, pp. 121-137.
- Post**, E., C. Pedersen, C.C. Wilmers, and M.C. Forchhammer, 2008: Warming, plant phenology and the spatial dimension of trophic mismatch for large herbivores. *Proceedings of the Royal Society B*, **275(1646)**, 2005-2013.
- Post**, E., M.C. Forchhammer, M.S. Bret-Harte, T.V. Callaghan, T.R. Christensen, B. Elberling, A.D. Fox, O. Gilg, D.S. Hik, T.T. Hoye, R.A. Ims, E. Jeppesen, D.R. Klein, J. Madsen, A.D. McGuire, S. Rysgaard, D.E. Schindler, I. Stirling, M.P. Tamstorf, N.J.C. Tyler, R. van der Wal, J. Welker, P.A. Wookey, N.M. Schmidt, and P. Aastrup, 2009: Ecological dynamics across the Arctic associated with recent climate change. *Science*, **325(5946)**, 1355-1358.
- Potts**, S.G., J.C. Biesmeijer, C. Kremen, P. Neumann, O. Schweiger, and W.E. Kunin, 2010: Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution*, **25(6)**, 345-353.
- Potvin**, C., F. Chapin, A. Gonzalez, P. Leadley, P. Reich, and J. Roy, 2007: Plant biodiversity and responses to elevated carbon dioxide. In: *Terrestrial Ecosystems in a Changing World* [Canadell, J.G., D.E. Pataki, and L.F. Pitelka (eds.)]. Global Change – The IGBP Series, Springer-Verlag, Berlin, Heidelberg, Germany, pp. 103-112.
- Pounds**, J.A., M.R. Bustamante, L.A. Coloma, J.A. Consuegra, M.P.L. Fogden, P.N. Foster, E. La Marca, K.L. Masters, A. Merino-Viteri, R. Puschendorf, S.R. Ron, G.A. Sanchez-Azofeifa, C.J. Still, and B.E. Young, 2006: Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature*, **439(7073)**, 161-167.
- Powell**, T.L., D.R. Galbraith, B.O. Christoffersen, A. Harper, H.M.A. Imbuzeiro, L. Rowland, S. Almeida, P.M. Brando, A. Carlos Lola da Costa, M. Heil Costa, N.M. Levine, Y. Malhi, S.R. Saleska, E. Sotta, M. Williams, P. Meir, and P.R. Moorcroft, 2013: Confronting model predictions of carbon fluxes with measurements of Amazon forests subjected to experimental drought. *New Phytologist*, **200**, 350-364.
- Power**, S.A., E.R. Green, C.G. Barker, J.N.B. Bell, and M.R. Ashmore, 2006: Ecosystem recovery: heathland response to a reduction in nitrogen deposition. *Global Change Biology*, **12(7)**, 1241-1252.
- Prentice**, I.C. and S.P. Harrison, 2009: Ecosystem effects of CO₂ concentration: evidence from past climates. *Climate of the Past*, **5(3)**, 297-307.
- Prentice**, I.C., J. Guiot, B. Huntley, D. Jolly, and R. Cheddadi, 1996: Reconstructing biomes from palaeoecological data: a general method and its application to European pollen data at 0 and 6 ka. *Climate Dynamics*, **12**, 185-194.
- Prentice**, I.C., S.P. Harrison, and P.J. Bartlein, 2011: Global vegetation and terrestrial carbon cycle changes after the last ice age. *New Phytologist*, **189(4)**, 988-998.
- Prieto**, P., J. Penuelas, J. Llusia, D. Asensio, and M. Estiarte, 2009: Effects of long-term experimental night-time warming and drought on photosynthesis, Fv/Fm and stomatal conductance in the dominant species of a Mediterranean shrubland. *Acta Physiologicae Plantarum*, **31(4)**, 729-739.
- Primack**, R.B., I. Ibáñez, H. Higuchi, S.D. Lee, A.J. Miller-Rushing, A.M. Wilson, and J.A. Silander Jr., 2009: Spatial and interspecific variability in phenological responses to warming temperatures. *Biological Conservation*, **142(11)**, 2569-2577.
- Prince**, S.D., K.J. Wessels, C.J. Tucker, and S.E. Nicholson, 2007: Desertification in the Sahel: a reinterpretation of a reinterpretation. *Global Change Biology*, **13(7)**, 1308-1313.
- Pringle**, C.M., 2001: Hydrologic connectivity and the management of biological reserves: a global perspective. *Ecological Applications*, **11(4)**, 981-998.
- Prost**, S., R.P. Guralnick, E. Waltari, V.B. Fedorov, E. Kuzmina, N. Smirnov, T. Van Kolschoten, M. Hofreiter, and K. Vrieling, 2013: Losing ground: past history and future fate of Arctic small mammals in a changing climate. *Global Change Biology*, **19(6)**, 1854-1864.
- Prowse**, T.D. and K. Brown, 2010: Hydro-ecological effects of changing Arctic river and lake ice covers: a review. *Hydrology Research*, **41(6)**, 454-461.
- Prugh**, L.R., K.E. Hodges, A.R.E. Sinclair, and J.S. Brashares, 2008: Effect of habitat area and isolation on fragmented animal populations. *Proceedings of the National Academy of Sciences of the United States of America*, **105(52)**, 20770-20775.
- Pulido**, F., 2007: Phenotypic changes in spring arrival: evolution, phenotypic plasticity, effects of weather and condition. *Climate Research*, **35(1-2)**, 5-23.
- Racine**, C., R. Jandt, C. Meyers, and J. Dennis, 2004: Tundra fire and vegetation change along a hillslope on the Seward Peninsula, Alaska, U.S.A. *Arctic, Antarctic, and Alpine Research*, **36(1)**, 1-10.
- Raffa**, K.F., B.H. Aukema, B.J. Bentz, A.L. Carroll, J.A. Hicke, M.G. Turner, and W.H. Romme, 2008: Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *BioScience*, **58(6)**, 501-517.
- Raghu**, S., R.C. Anderson, C.C. Daehler, A.S. Davis, R.N. Wiedenmann, D. Simberloff, and R.N. Mack, 2006: Adding biofuels to the invasive species fire? *Science*, **313(5794)**, 1742-1742.
- Rahel**, F.J. and J.D. Olden, 2008: Assessing the effects of climate change on aquatic invasive species. *Conservation Biology*, **22(3)**, 521-533.
- Randerson**, J.T., H. Liu, M.G. Flanner, S.D. Chambers, Y. Jin, P.G. Hess, G. Pfister, M.C. Mack, K.K. Treseder, L.R. Welp, F.S. Chapin, J.W. Harden, M.L. Goulden, E. Lyons, J.C. Neff, E.A.G. Schuur, and C.S. Zender, 2006: The impact of boreal forest fire on climate warming. *Science*, **314(5802)**, 1130-1132.
- Randin**, C.F., R. Engler, S. Normand, M. Zappa, N.E. Zimmermann, P.B. Pearman, P. Vittoz, W. Thuiller, and A. Guisan, 2009: Climate change and plant distribution: local models predict high-elevation persistence. *Global Change Biology*, **15(6)**, 1557-1569.
- Raupach**, M.R., J.G. Canadell, and C. Le Quéré, 2008: Anthropogenic and biophysical contributions to increasing atmospheric CO₂ growth rate and airborne fraction. *Biogeosciences*, **5(6)**, 1601-1613.
- Ravi**, S., D.D. Breshears, T.E. Huxman, and P. D'Odorico, 2010: Land degradation in drylands: interactions among hydrologic-aeolian erosion and vegetation dynamics. *Geomorphology*, **116(3-4)**, 236-245.
- Rawson**, D.M., G.M. Reid, and R.E. Lloyd, 2011: Conservation rationale, research applications and techniques in the cryopreservation of lower vertebrate biodiversity from marine and freshwater environments. *International Zoo Yearbook*, **45**, 108-123.
- Raxworthy**, C.J., R.G. Pearson, N. Rabibisoa, A.M. Rakotondrzafay, J.B. Ramanamanjato, A.P. Raselimanana, S. Wu, R.A. Nussbaum, and D.A. Stone, 2008: Extinction vulnerability of tropical montane endemism from warming and upslope displacement: a preliminary appraisal for the highest massif in Madagascar. *Global Change Biology*, **14(8)**, 1703-1720.
- Ray**, D., D. Nepstad, and P. Moutinho, 2005: Micrometeorological and canopy controls of flammability in mature and disturbed forests in an east-central Amazon landscape. *Ecological Applications*, **15(5)**, 1664-1678.
- Ray**, D.K., N. Ramankutty, N.D. Mueller, P.C. West, and J.A. Foley, 2012: Recent patterns of crop yield growth and stagnation. *Nature Communications*, **3**, 1293, doi:10.1038/ncomms2296.

- Réale, D., A.G. McAdam, S. Boutin, and D. Berteaux, 2003:** Genetic and plastic responses of a northern mammal to climate change. *Proceedings of the Royal Society B*, **270(1515)**, 591-596.
- Reed, T.E., V. Grotan, S. Jenouvrier, B.E. Saether, and M.E. Visser, 2013:** Population growth in a wild bird is buffered against phenological mismatch. *Science*, **340(6131)**, 488-491.
- Regnier, C., B. Fontaine, and P. Bouchet, 2009:** Not knowing, not recording, not listing: numerous unnoticed mollusk extinctions. *Conservation Biology*, **23(5)**, 1214-1221.
- Rehfeldt, G.E. and B.C. Jaquish, 2010:** Ecological impacts and management strategies for western larch in the face of climate-change. *Mitigation and Adaptation Strategies for Global Change*, **15(3)**, 283-306.
- Rehfeldt, G.E., N.L. Crookston, C. Saenz-Romero, and E.M. Campbell, 2012:** North American vegetation model for land-use planning in a changing climate: a solution to large classification problems. *Ecological Applications*, **22(1)**, 119-141.
- Reich, P.B., 2009:** Elevated CO₂ reduces losses of plant diversity caused by nitrogen deposition. *Science*, **326(5958)**, 1399-1402.
- Reich, P.B., S.E. Hobbie, T. Lee, D.S. Ellsworth, J.B. West, D. Tilman, J.M.H. Knops, S. Naeem, and J. Trost, 2006:** Nitrogen limitation constrains sustainability of ecosystem response to CO₂. *Nature*, **440(7086)**, 922-925.
- Reidy Liermann, C., C. Nilsson, J. Robertson, and R.Y. Ng, 2012:** Implications of dam obstruction for global freshwater fish diversity. *BioScience*, **62(6)**, 539-548.
- Reist, J.D., F.J. Wrona, T.D. Prowse, M. Power, J.B. Dempson, R.J. Beamish, J.R. King, T.J. Carmichael, and C.D. Sawatzky, 2006:** General effects of climate change on Arctic fishes and fish populations. *Ambio*, **35(7)**, 370-380.
- Renwick, A.R., D. Massimino, S.E. Newson, D.E. Chamberlain, J.W. Pearce-Higgins, and A. Johnston, 2012:** Modelling changes in species' abundance in response to projected climate change. *Diversity and Distributions*, **18(2)**, 121-132.
- Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, and P. Rafaj, 2011:** RCP 8.5 – a scenario of comparatively high greenhouse gas emissions. *Climatic Change*, **109**, 33-57.
- Ricciardi, A. and D. Simberloff, 2009:** Assisted colonization is not a viable conservation strategy. *Trends in Ecology & Evolution*, **24(5)**, 248-253.
- Richardson, D.M., J.J. Hellmann, J.S. McLachlan, D.F. Sax, M.W. Schwartz, P. Gonzalez, E.J. Brennan, A. Camacho, T.L. Root, O.E. Sala, S.H. Schneider, D.M. Ashe, J.R. Clark, R. Early, J.R. Eiterson, E.D. Fielder, J.L. Gill, B.A. Minter, S. Polasky, H.D. Safford, A.R. Thompson, and M. Vellend, 2009:** Multidimensional evaluation of managed relocation. *Proceedings of the National Academy of Sciences of the United States of America*, **106(24)**, 9721-9724.
- Ridgwell, A., J.S. Singarayer, A.M. Hetherington, and P.J. Valdes, 2009:** Tackling regional climate change by leaf albedo bio-geoengineering. *Current Biology*, **19(2)**, 146-150.
- Rieley, J.O., R.A.J. Wüst, J. Jauhainen, S.E. Page, J.H.M. Wösten, A. Hooijer, E. Siegert, S.H. Limin, H. Vasander, and M. Stahlhut, 2008:** Tropical peatlands: carbon stores, carbon gas emissions and contribution to climate change processes. In: *Peatlands and Climate Change* [Strack, M. (ed.)]. International Peat Society, Jyväskylä, Finland, pp. 148-181.
- Roberts, S.P.M., S.G. Potts, J. Biesmeijer, M. Kuhlmann, B. Kunin, and R. Ohlemüller, 2011:** Assessing continental-scale risks for generalist and specialist pollinating bee species under climate change. *BioRisk*, **6**, 1-18.
- Robinet, C. and A. Roques, 2010:** Direct impacts of recent climate warming on insect populations. *Integrative Zoology*, **5(2)**, 132-142.
- Rocha, A.V. and G.R. Shaver, 2011:** Burn severity influences postfire CO₂ exchange in arctic tundra. *Ecological Applications*, **21(2)**, 477-489.
- Rodriguez-Labajos, B., 2013:** Climate and change, ecosystems services and costs of action and inaction: scoping the interface. *Wiley Interdisciplinary Review: Climate Change*, **4(6)**, 555-573.
- Rohde, R.F. and M.T. Hoffman, 2012:** The historical ecology of Namibian rangelands: Vegetation change since 1876 in response to local and global drivers. *Science of the Total Environment*, **416**, 276-288.
- Roland, C.A., J.H. Schmidt, and E.F. Nicklen, 2013:** Landscape-scale patterns in tree occupancy and abundance in subarctic Alaska. *Ecological Monographs*, **83(1)**, 19-48.
- Romanovsky, V.E., S.L. Smith, and H.H. Christiansen, 2010:** Permafrost thermal state in the polar Northern Hemisphere during the International Polar Year 2007-2009: a synthesis. *Permafrost and Periglacial Processes*, **21(2)**, 106-116.
- Romijn, E., M. Herold, L. Kooistra, D. Murdiyarsa, and L. Verchot, 2012:** Assessing capacities of non-Annex I countries for national forest monitoring in the context of REDD+. *Environmental Science and Policy*, **19-20**, 33-48.
- Root, T.L., J.T. Price, K.R. Hall, S.H. Schneider, C. Rosenzweig, and J.A. Pounds, 2003:** Fingerprints of global warming on wild animals and plants. *Nature*, **421(6918)**, 57-60.
- Rosenheim, J.A. and B.E. Tabashnik, 1991:** Influence of generation time on the response to selection. *American Naturalist*, **137(4)**, 527-541.
- Rosenzweig, C., G. Casassa, D.J. Karoly, A. Imeson, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin, and P. Tryjanowski, 2007:** Assessment of observed changes and responses in natural and managed systems. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 79-131.
- Rosset, V., A. Lehmann, and B. Oertli, 2010:** Warmer and richer? Predicting the impact of climate warming on species richness in small temperate waterbodies. *Global Change Biology*, **16(8)**, 2376-2387.
- Rössler, M., 2006:** World heritage cultural landscapes: a UNESCO flagship programme 1992-2006. *Landscape Research*, **31(4)**, 333-353.
- Rounsevell, M.D.A. and D.S. Reay, 2009:** Land use and climate change in the UK. *Land Use Policy*, **26(Suppl 1)**, S160-S169.
- Roux, D.J., J.L. Nel, P.J. Ashton, A.R. Deacon, F.C. de Moor, D. Hardwick, L. Hill, C.J. Kleynhans, G.A. Maree, J. Moolman, and R.J. Scholes, 2008:** Designing protected areas to conserve riverine biodiversity: lessons from a hypothetical redesign of the Kruger National Park. *Biological Conservation*, **141(1)**, 100-117.
- Rowe, R.J., J.A. Finarelli, and E.A. Rickart, 2010:** Range dynamics of small mammals along an elevational gradient over an 80-year interval. *Global Change Biology*, **16(11)**, 2930-2943.
- Rubidge, E.M., W.B. Monahan, J.L. Parra, S.E. Cameron, and J.S. Brashares, 2011:** The role of climate, habitat, and species co-occurrence as drivers of change in small mammal distributions over the past century. *Global Change Biology*, **17(2)**, 696-708.
- Ruiz-Labourdette, D., M.F. Schmitz, and F.D. Pineda, 2013:** Changes in tree species composition in Mediterranean mountains under climate change: indicators for conservation planning. *Ecological Indicators*, **24**, 310-323.
- Rupp, T.S., F.S. Chapin, and A. Starfield, 2001:** Modeling the influence of topographic barriers on treeline advance at the forest-tundra ecotone in northwestern Alaska. *Climatic Change*, **48(2)**, 399-416.
- Russell, L.M., P.J. Rasch, G.M. Mace, R.B. Jackson, J. Shepherd, P. Liss, M. Leinen, D. Schimel, N.E. Vaughan, A.C. Janetos, P.W. Boyd, R.J. Norby, K. Caldeira, J. Merikanto, P. Artaxo, J. Melillo, and M.G. Morgan, 2012:** Ecosystem impacts of geoengineering: a review for developing a science plan. *Ambio*, **41(4)**, 350-369.
- Rustad, L.E., 2008:** The response of terrestrial ecosystems to global climate change: towards an integrated approach. *Science of the Total Environment*, **404(2-3)**, 222-235.
- Ryan, M.G., M.E. Harmon, R.A. Birdsey, C.P. Giardina, L.S. Heath, R.A. Houghton, R.B. Jackson, D.C. McKinley, J.F. Morrison, B.C. Murray, D.E. Pataki, and K.E. Skog, 2010:** A synthesis of the science on forests and carbon for U.S. forests. *Issues in Ecology*, **13**, 1-16.
- Saatchi, S., S. Asefi-Najafabady, Y. Malhi, L.E.O.C. Aragão, L.O. Anderson, R.B. Myneni, and R. Nemani, 2013:** Persistent effects of a severe drought on Amazonian forest canopy. *Proceedings of the National Academy of Sciences of the United States of America*, **110(2)**, 565-570.
- Saino, N., D. Rubolini, E. Lehikoinen, L.V. Sokolov, A. Bonisoli-Alquati, R. Ambrosini, G. Boncoraglio, and A.P. Moller, 2009:** Climate change effects on migration phenology may mismatch brood parasitic cuckoos and their hosts. *Biology Letters*, **5(4)**, 539-541.
- Sala, O.E., W.J. Parton, L.A. Joyce, and W.K. Lauenroth, 1988:** Primary production of the Central Grassland Region of the United States. *Ecology*, **69(1)**, 10-45.
- Salamin, N., R.O. Wuest, S. Lavergne, W. Thuiller, and P.B. Pearman, 2010:** Assessing rapid evolution in a changing environment. *Trends in Ecology & Evolution*, **25(12)**, 692-698.
- Salzmann, U., A.M. Haywood, D.J. Lunt, P.J. Valdes, and D.J. Hill, 2008:** A new global biome reconstruction and data-model comparison for the Middle Pliocene. *Global Ecology and Biogeography*, **17(3)**, 432-447.
- Samanta, A., M.H. Costa, E.L. Nunes, S.A. Vieira, L. Xu, and R.B. Myneni, 2011:** Comment on "Drought-induced reduction in global terrestrial net primary production from 2000 through 2009". *Science*, **333(6046)**, 1093-c.
- Sandel, B. and E.M. Dangremond, 2012:** Climate change and the invasion of California by grasses. *Global Change Biology*, **18(1)**, 277-289.

- Sandel, B., L. Arge, B. Dalsgaard, R.G. Davies, K.J. Gaston, W.J. Sutherland, and J.C. Svenning, 2011: The influence of Late Quaternary climate-change velocity on species endemism. *Science*, **334**(6056), 660-664.
- Sankaran, M., N.P. Hanan, R.J. Scholes, J. Ratnam, D.J. Augustine, B.S. Cade, J. Gignoux, S.I. Higgins, X. Le Roux, F. Ludwig, J. Ardo, F. Banyikwa, A. Bronn, G. Bucini, K.K. Caylor, M.B. Coughenour, A. Diouf, W. Ekaya, C.J. Feral, E.C. February, P.G.H. Frost, P. Hiernaux, H. Hrabar, K.L. Metzger, H.H.T. Prins, S. Ringrose, W. Sea, J. Tews, J. Worden, and N. Zambatis, 2005: Determinants of woody cover in African savannas. *Nature*, **438**(7069), 846-849.
- Santini, L., M. Di Marco, P. Visconti, D. Baisero, L. Boitani, and C. Rondinini, 2013: Ecological correlates of dispersal distance in terrestrial mammals. *Hystrix, the Italian Journal of Mammalogy*, **24**(2), doi:10.4404/hystrix-24.2-8746.
- Sarau, C., C. Le Bohec, J.M. Durant, V.A. Vialanc, M. Gauthier-Clerc, D. Beaune, Y.-H. Park, N.G. Yoccoz, N.C. Stenseth, and Y. Le Maho, 2011: Reliability of flipper-banded penguins as indicators of climate change. *Nature*, **469**(7329), 203-206.
- Sardans, J., J. Penuelas, M. Estiarte, and P. Prieto, 2008a: Warming and drought alter C and N concentration, allocation and accumulation in a Mediterranean shrubland. *Global Change Biology*, **14**(10), 2304-2316.
- Sardans, J., J. Penuelas, P. Prieto, and M. Estiarte, 2008b: Changes in Ca, Fe, Mg, Mo, Na, and S content in a Mediterranean shrubland under warming and drought. *Journal of Geophysical Research: Biogeosciences*, **113**(G3), G03039, doi:10.1029/2008JG000795.
- Sardans, J., A. Rivas-Ubach, and J. Penuelas, 2012: The C:N:P stoichiometry of organisms and ecosystems in a changing world: a review and perspectives. *Perspectives in Plant Ecology Evolution and Systematics*, **14**(1), 33-47.
- Sarris, D., D. Christodoulakis, and C. Körner, 2011: Impact of recent climatic change on growth of low elevation eastern Mediterranean forest trees. *Climatic Change*, **106**(2), 203-223.
- Sato, H. and T. Ise, 2012: Effect of plant dynamic processes on African vegetation responses to climate change: analysis using the spatially explicit individual-based dynamic global vegetation model (SEIB-DGVM). *Journal of Geophysical Research: Biogeosciences*, **117**(G3), G03017, doi:10.1029/2012JG002056.
- Sauer, J., S. Domisch, C. Nowak, and P. Haase, 2011: Low mountain ranges: summit traps for montane freshwater species under climate change. *Biodiversity and Conservation*, **20**(13), 3133-3146.
- Saurral, R.I., V.R. Barros, and D.P. Lettenmaier, 2008: Land use impact on the Uruguay River discharge. *Geophysical Research Letters*, **35**(12), L12401.
- Schaefer, K., T.J. Zhang, L. Bruhwiler, and A.P. Barrett, 2011: Amount and timing of permafrost carbon release in response to climate warming. *Tellus Series B: Chemical and Physical Meteorology*, **63**(2), 165-180.
- Schaper, S.V., A. Dawson, P.J. Sharp, P. Gienapp, S.P. Caro, and M.E. Visser, 2012: Increasing temperature, not mean temperature, is a cue for avian timing of reproduction. *The American Naturalist*, **179**(2), E55-E69.
- Scheffer, M., 2009: *Critical Transitions in Nature and Society*. Princeton University Press, Princeton, NJ, USA, 400 pp.
- Scheffer, M., J. Bascompte, W.A. Brock, V. Brovkin, S.R. Carpenter, V. Dakos, H. Held, E.H. van Nes, M. Rietkerk, and G. Sugihara, 2009: Early-warning signals for critical transitions. *Nature*, **461**(7260), 53-59.
- Scheffer, M., M. Hirota, M. Holmgren, E.H. Van Nes, and F.S. Chapin III, 2012: Thresholds for boreal biome transitions. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(52), 21384-21389.
- Scheiter, S. and S.I. Higgins, 2009: Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modelling approach. *Global Change Biology*, **15**(9), 2224-2246.
- Schiffers, K., E.C. Bourne, S. Lavergne, W. Thuiller, and J.M.J. Travis, 2013: Limited evolutionary rescue of locally adapted populations facing climate change. *Philosophical Transactions of the Royal Society B*, **368**(1610), 20120083, doi:10.1098/rstb.2012.0083.
- Schippers, P., J. Verboom, C.C. Vos, and R. Jochem, 2011: Metapopulation shift and survival of woodland birds under climate change: will species be able to track? *Ecography*, **34**(6), 909-919.
- Schloss, C.A., T.A. Nunez, and J.J. Lawler, 2012: Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(22), 8606-8611.
- Schneider, A., M.A. Friedl, and D. Potere, 2009: A new map of global urban extent from MODIS satellite data. *Environmental Research Letters*, **4**(4), 044003, doi:10.1088/1748-9326/4/4/044003.
- Schneider, C., 2003: The influence of spatial scale on quantifying insect dispersal: an analysis of butterfly data. *Ecological Entomology*, **28**(2), 252-256.
- Schnitzler, A., B.W. Hale, and E.M. Alsum, 2007: Examining native and exotic species diversity in European riparian forests. *Biological Conservation*, **138**(1-2), 146-156.
- Scholes, R.J. and S.R. Archer, 1997: Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics*, **28**, 517-544.
- Scholze, M., W. Knorr, N.W. Arnell, and I.C. Prentice, 2006: A climate-change risk analysis for world ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, **103**(35), 13116-13120.
- Schulte, P., L. Alegret, I. Arenillas, J.A. Arz, P.J. Barton, P.R. Bown, T.J. Bralower, G.L. Christeson, P. Claeys, C.S. Cockell, G.S. Collins, A. Deutsch, T.J. Goldin, K. Goto, J.M. Grajales-Nishimura, R.A.F. Grieve, S.P.S. Gulick, K.R. Johnson, W. Kiessling, C. Koeberl, D.A. Kring, K.G. MacLeod, T. Matsui, J. Melosh, A. Montanari, J.V. Morgan, C.R. Neal, D.J. Nichols, R.D. Norris, E. Pierazzo, G. Ravizza, M. Rebolledo-Vieyra, W.U. Reimold, E. Robin, T. Salge, R.P. Speijer, A.R. Sweet, J. Urrutia-Fucugauchi, V. Vajda, M.T. Whalen, and P.S. Willumsen, 2010: The Chicxulub Asteroid impact and mass extinction at the Cretaceous-Paleogene Boundary. *Science*, **327**(5970), 1214-1218.
- Schultz, M.G., A. Heil, J.J. Hoelzemann, A. Spessa, K. Thonicke, J.G. Goldammer, A.C. Held, J.M.C. Pereira, and M. van het Bolscher, 2008: Global wildland fire emissions from 1960 to 2000. *Global Biogeochemical Cycles*, **22**(2), GB2002, doi:10.1029/2007GB003031.
- Schuur, E.A.G., J. Bockheim, J.G. Canadell, E. Euskirchen, C.B. Field, S.V. Goryachkin, S. Hagemann, P. Kuhry, P.M. Lafleur, H. Lee, G. Mazhitova, F.E. Nelson, A. Rinke, V.E. Romanovsky, N. Shiklomanov, C. Tarnocai, S. Venevsky, J.G. Vogel, and S.A. Zimov, 2008: Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. *BiScience*, **58**(8), 701-714.
- Schuur, E.A.G., J.G. Vogel, K.G. Crummer, H. Lee, J.O. Sickman, and T.E. Osterkamp, 2009: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature*, **459**(7246), 556-559.
- Schuur, E.A.G., B.W. Abbott, W.B. Bowden, V. Brovkin, P. Camill, J.G. Canadell, J.P. Chanton, F.S. Chapin III, T.R. Christensen, P. Ciais, B.T. Crosby, C.I. Czimczik, G. Grosse, J. Harden, D.J. Hayes, G. Hugelius, J.D. Jastrow, J.B. Jones, T. Kleinen, C.D. Koven, G. Krinner, P. Kuhry, D.M. Lawrence, A.D. McGuire, S.M. Natali, J.A. O'Donnell, C.L. Ping, W.J. Riley, A. Rinke, V.E. Romanovsky, A.B.K. Sannel, C. Schädel, K. Schaefer, J. Sky, Z.M. Subin, C. Tarnocai, M.R. Turetsky, M.P. Waldrop, K.M. Walter Anthony, K.P. Wickland, C.J. Wilson, and S.A. Zimov, 2013: Expert assessment of vulnerability of permafrost carbon to climate change. *Climate Change*, **119**, 359-374. doi:10.1007/s10584-013-0730-7.
- Schwaiger, H.P. and D.N. Bird, 2010: Integration of albedo effects caused by land use change into the climate balance: should we still account in greenhouse gas units? *Forest Ecology and Management*, **260**(3), 278-286.
- Schweiger, O., J. Settele, O. Kudrna, S. Klotz, and I. Kühn, 2008: Climate change can cause spatial mismatch of trophically interacting species. *Ecology*, **89**(12), 3472-3479.
- Schweiger, O., J.C. Biesmeijer, R. Bommarco, T. Hickler, P.E. Hulme, S. Klotz, I. Kuehn, M. Moora, A. Nielsen, R. Ohlemüller, T. Petanidou, S.G. Potts, P. Pyšek, J.C. Stout, M.T. Sykes, T. Tscheulin, M. Vila, G.-R. Walther, C. Westphal, M. Winter, M. Zobel, and J. Settele, 2010: Multiple stressors on biotic interactions: how climate change and alien species interact to affect pollination. *Biological Reviews*, **85**(4), 777-795.
- Schweiger, O., A. Harpke, R. Heikkinen, T. Hickler, I. Kühn, J. Pöry, and J. Settele, 2012: Increasing range mismatching of interacting species under global change is related to their ecological characteristics. *Global Ecology and Biogeography*, **21**(1), 88-99.
- Seaquist, J.W., T. Hickler, L. Eklundh, J. Ardö, and B.W. Heumann, 2009: Disentangling the effects of climate and people on Sahel vegetation dynamics. *Biogeosciences*, **6**(3), 469-477.
- Searchinger, T., R. Heimlich, R.A. Houghton, F.X. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.H. Yu, 2008: Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**(5867), 1238-1240.
- Seidel, D.J., Q. Fu, W.J. Randel, and T.J. Reichler, 2008: Widening of the tropical belt in a changing climate. *Nature Geoscience*, **1**(1), 21-24.
- Sekercioglu, C.H., R.B. Primack, and J. Wormworth, 2012: The effects of climate change on tropical birds. *Biological Conservation*, **148**(1), 1-18.
- Selsted, M.B., L. van der Linden, A. Ibrom, A. Michelsen, K.S. Larsen, J.K. Pedersen, T.N. Mikkelsen, K. Pilegaard, C. Beier, and P. Ambus, 2012: Soil respiration is stimulated by elevated CO₂ and reduced by summer drought: three years of measurements in a multifactor ecosystem manipulation experiment in a temperate heathland (CLIMAITE). *Global Change Biology*, **18**(4), 1216-1230.

- Seppälä, R., 2009: A global assessment on adaptation of forests to climate change. *Scandinavian Journal of Forest Research*, **24**(6), 469-472.
- Seppelt, R., C.F. Dormann, F.V. Eppink, S. Lautenbach, and S. Schmidt, 2011: A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. *Journal of Applied Ecology*, **48**(3), 630-636.
- Serreze, M.C. and J.A. Francis, 2006: The Arctic amplification debate. *Climate Change*, **76**(3), 241-264.
- Settele, J. and E. Kühn, 2009: Insect conservation. *Science*, **325**(5936), 41-42.
- Settele, J., O. Kudrna, A. Harpke, I. Kühn, C. Van Swaay, R. Verovnik, M. Warren, M. Wiemers, J. Hanspach, T. Hickler, E. Kühn, I. Van Halder, K. Veling, A. Vliegthart, I. Wynhoff, and O. Schweiger, 2008: Special Issue: Climatic Risk Atlas of European Butterflies. *BioRisk*, **1**, 1-710, doi:10.3897/biorisk.1.
- Settele, J., L. Penev, T. Georgiev, R. Grabaum, V. Grobelnik, V. Hammen, S. Klotz, M. Kotarac, and I. Kühn (eds.), 2010a: *Atlas of Biodiversity Risk*. Pensoft Publishers, Sofia, Bulgaria, 300 pp.
- Settele, J., M. Zobel, J.H. Spangenberg, S. Klotz, V. Hammen, and I. Kühn, 2010b: Designing projects for integrated research – the ALARM experience. In: *Atlas of Biodiversity Risk* [Settele, J., L. Penev, T. Georgiev, R. Grabaum, V. Grobelnik, V. Hammen, S. Klotz, M. Kotarac, and I. Kühn (eds.)]. Pensoft Publishers, Sofia, Bulgaria, pp. 208-209.
- Shakesby, R.A., 2011: Post-wildfire soil erosion in the Mediterranean: review and future research directions. *Earth-Science Reviews*, **105**(3-4), 71-100.
- Shanin, V.N., A.S. Komarov, A.V. Mikhailov, and S.S. Bykhovets, 2011: Modelling carbon and nitrogen dynamics in forest ecosystems of Central Russia under different climate change scenarios and forest management regimes. *Ecological Modelling*, **222**(14), 2262-2275.
- Sharma, S., S. Couturier, and S.D. Cote, 2009: Impacts of climate change on the seasonal distribution of migratory caribou. *Global Change Biology*, **15**(10), 2549-2562.
- Sharp, B.R. and D.M.J.S. Bowman, 2004: Patterns of long-term woody vegetation change in a sandstone-plateau savanna woodland, Northern Territory, Australia. *Journal of Tropical Ecology*, **20**(3), 259-270.
- Shaw, M.R., E.S. Zavaleta, N.R. Chiariello, E.E. Cleland, H.A. Mooney, and C.B. Field, 2002: Grassland responses to global environmental changes suppressed by elevated CO₂. *Science*, **298**(5600), 1987-1990.
- Sheldon, F., S.E. Bunn, J.M. Hughes, A.H. Arthington, S.R. Balcombe, and C.S. Fellows, 2010: Ecological roles and threats to aquatic refugia in arid landscapes: dryland river waterholes. *Marine and Freshwater Research*, **61**(8), 885-895.
- Shimazaki, M., I. Tsuyama, E. Nakazono, K. Nakao, M. Konoshima, N. Tanaka, and T. Nakashizuka, 2012: Fine-resolution assessment of potential refugia for a dominant fir species (*Abies mariesii*) of subalpine coniferous forests after climate change. *Plant Ecology*, **213**(4), 603-612.
- Shimoda, Y., M.E. Azim, G. Perhar, M. Ramin, M.A. Kenney, S. Sadraddini, A. Gudimov, and G.B. Arhonditsis, 2011: Our current understanding of lake ecosystem response to climate change: what have we really learned from the north temperate deep lakes? *Journal of Great Lakes Research*, **37**(1), 173-193.
- Shinoda, M., G.U. Nachinshonhor, and M. Nemoto, 2010: Impact of drought on vegetation dynamics of the Mongolian steppe: a field experiment. *Journal of Arid Environments*, **74**(1), 63-69.
- Shiogama, H., S. Emori, N. Hanasaki, M. Abe, Y. Masutomi, K. Takahashi, and T. Nakawa, 2011: Observational constraints indicate risk of drying in the Amazon basin. *Nature Communications*, **2**, 253, doi:10.1038/ncomms1252.
- Silva, L.C.R. and M. Anand, 2013: Probing for the influence of atmospheric CO₂ and climate change on forest ecosystems across biomes. *Global Ecology and Biogeography*, **22**(1), 83-92.
- Silva, L.C.R., M. Anand, and M.D. Leithead, 2010: Recent widespread tree growth decline despite increasing atmospheric CO₂. *PLoS One*, **5**(7), e11543, doi:10.1371/journal.pone.0011543.
- Silvestrini, R., B. Soares-Filho, D. Nepstad, M.T. Coe, H. Rodrigues, and R. Assuncao, 2011: Simulating fire regimes in the Amazon in response to climate change and deforestation. *Ecological Applications*, **21**(5), 1573-1590.
- Simberloff, D., J.-L. Martin, P. Genovesi, V. Maris, D.A. Wardle, J. Aronson, F. Courchamp, B. Galil, E. Garcia-Berthou, M. Pascal, P. Pyšek, R. Sousa, E. Tabacchi, and M. Vilà, 2013: Impacts of biological invasions: what's what and the way forward. *Trends in Ecology & Evolution*, **28**(1), 58-66.
- Sinervo, B., F. Mendez-de-la-Cruz, D.B. Miles, B. Heulin, E. Bastiaans, M.V.S. Cruz, R. Lara-Resendiz, N. Martinez-Mendez, M.L. Calderon-Espinosa, R.N. Meza-Lazaro, H. Gadsden, L.J. Avila, M. Morando, I.J. De la Riva, P.V. Sepulveda, C.F.D. Rocha, N. Ibarquengoytia, C.A. Puntriano, M. Massot, V. Lepetz, T.A. Oksanen, D.G. Chapple, A.M. Bauer, W.R. Branch, J. Clobert, and J.W. Sites, 2010: Erosion of lizard diversity by climate change and altered thermal niches. *Science*, **328**(5980), 894-899.
- Singer, M.C. and C. Parmesan, 2010: Phenological asynchrony between herbivorous insects and their hosts: signal of climate change or pre-existing adaptive strategy? *Philosophical Transactions of the Royal Society B*, **365**(1555), 3161-3176.
- Singh, A., S. Unnikrishnan, N. Naik, and K. Duvvuri, 2013: Role of India's forest in climate change mitigation through the CDM and REDD+. *Journal of Environmental Planning and Management*, **56**, 61-87.
- Sitch, S., P.M. Cox, W.J. Collins, and C. Huntingford, 2007: Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature*, **448**(7155), 791-794.
- Sitch, S., C. Huntingford, N. Gedney, P.E. Levy, M. Lomas, S.L. Piao, R. Betts, P. Ciais, P. Cox, P. Friedlingstein, C.D. Jones, I.C. Prentice, and F.I. Woodward, 2008: Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Global Change Biology*, **14**(9), 2015-2039.
- Smallwood, K.S., 2007: Estimating wind turbine-caused bird mortality. *Journal of Wildlife Management*, **71**(8), 2781-2791.
- Smit, B., I. Burton, R.J.T. Klein, and J. Wandel, 2000: An anatomy of adaptation to climate change and variability. *Climatic Change*, **45**(1), 223-251.
- Smit, B., O. Pilifosova, I. Burton, B. Challenger, S. Huq, R.J.T. Klein, G. Yohe, N. Adger, T. Downing, E. Harvey, S. Kane, M. Parry, M. Skinner, J. Smith, and J. Wandel, 2007: Adaptation to climate change in the context of sustainable development and equity. In: *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 879-912.
- Smith, A.L., N. Hewitt, N. Klenk, D.R. Bazely, N. Yan, S. Wood, I. Henriques, J.I. MacLellan, and C. Lipsig-Mummé, 2012: Effects of climate change on the distribution of invasive alien species in Canada: a knowledge synthesis of range change projections in a warming world. *Environmental Reviews*, **20**(1), doi:10.1139/a11-020.
- Smith, L.C., Y. Sheng, G.M. MacDonald, and L.D. Hinzman, 2005: Disappearing Arctic lakes. *Science*, **308**(5727), 1429-1429.
- Smith, S.J. and T.M.L. Wigley, 2006: Multi-gas forcing stabilization with minicam. *The Energy Journal*, **27** (S13), 373-391.
- Smol, J.P. and M.S.V. Douglas, 2007a: From controversy to consensus: making the case for recent climate using lake sediments. *Frontiers in Ecology and the Environment*, **5**(9), 466-474.
- Smol, J.P. and M.S.V. Douglas, 2007b: Crossing the final ecological threshold in high Arctic ponds. *Proceedings of the National Academy of Sciences of the United States of America*, **104**(30), 12395-12397.
- Snyman, H.A. and H.J. Fouché, 1993: Estimating seasonal herbage production of a semi-arid grassland based on veld condition, rainfall, and evapotranspiration. *African Journal of Range and Forage Science*, **10**(1), 21-24.
- Soares-Filho, B., P. Moutinho, D. Nepstad, A. Anderson, H. Rodrigues, R. Garcia, L. Dietzsch, F. Merry, M. Bowman, L. Hissa, R. Silvestrini, and C. Maretti, 2010: Role of Brazilian Amazon protected areas in climate change mitigation. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(24), 10821-10826.
- Soares-Filho, B., R. Silvestrini, D. Nepstad, P. Brando, H. Rodrigues, A. Alencar, M. Coe, C. Locks, L. Lima, L. Hissa, and C. Stickler, 2012: Forest fragmentation, climate change and understory fire regimes on the Amazonian landscapes of the Xingu headwaters. *Landscape Ecology*, **27**(4), 585-598.
- Sobek-Swant, S., J.C. Crosthwaite, D.B. Lyons, and B.J. Sinclair, 2012: Could phenotypic plasticity limit an invasive species? Incomplete reversibility of mid-winter deacclimation in emerald ash borer. *Biological Invasions*, **14**(1), 115-125.
- Sodhi, N.S., D. Bickford, A.C. Diesmos, T.M. Lee, L.P. Koh, B.W. Brook, C.H. Sekercioglu, and C.J.A. Bradshaw, 2008: Measuring the meltdown: drivers of global amphibian extinction and decline. *PLoS One*, **3**(2), e1636, doi:10.1371/journal.pone.0001636.
- Soja, A.J., N.M. Tchepakova, N.H.F. French, M.D. Flannigan, H.H. Shugart, B.J. Stocks, A.I. Sukhinin, E.I. Parfenova, F.S. Chapin, and P.W. Stackhouse, 2007: Climate-induced boreal forest change: predictions versus current observations. *Global and Planetary Change*, **56**(3-4), 274-296.
- Sokolov, L., 2006: Effect of global warming on the timing of migration and breeding of passerine birds in the 20th century. *Entomological Review Supplement*, **86**(1), S59-S81.

- Soliani, C., L. Gallo, and P. Marchelli, 2012:** Phylogeography of two hybridizing southern beeches (*Nothofagus* spp.) with different adaptive abilities. *Tree Genetics & Genomes*, **8(4)**, 659-673.
- Sommer, J.H., H. Kreft, G. Kier, W. Jetz, J. Mutke, and W. Barthlott, 2010:** Projected impacts of climate change on regional capacities for global plant species richness. *Proceedings of the Royal Society B*, **277(1692)**, 2271-2280.
- Søndergaard, M., J.P. Jensen, and E. Jeppesen, 2003:** Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia*, **506(1-3)**, 135-145.
- Sovacool, B.K., 2009:** Contextualizing avian mortality: a preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. *Energy Policy*, **32(6)**, 2241-2248.
- Sowerby, A., B.A. Emmett, A. Tietema, and C. Beier, 2008:** Contrasting effects of repeated summer drought on soil carbon efflux in hydric and mesic heathland soils. *Global Change Biology*, **14(10)**, 2388-2404.
- Sowerby, A., B.A. Emmett, D. Williams, C. Beier, and C.D. Evans, 2010:** The response of dissolved organic carbon (DOC) and the ecosystem carbon balance to experimental drought in a temperate shrubland. *European Journal of Soil Science*, **61(5)**, 697-709.
- Spracklen, D.V., B. Bonn, and K.S. Carslaw, 2008:** Boreal forests, aerosols and the impacts on clouds and climate. *Philosophical Transactions of the Royal Society A*, **366(1885)**, 4613-4626.
- Stahlschmidt, Z.R., D.F. DeNardo, J.N. Holland, B.P. Kotler, and M. Kruse-Peeples, 2011:** Tolerance mechanisms in North American deserts: biological and societal approaches to climate change. *Journal of Arid Environments*, **75(8)**, 681-687.
- Staver, A.C., S. Archibald, and S.A. Levin, 2011:** The global extent and determinants of savanna and forest as alternative biome states. *Science*, **334(6053)**, 230-232.
- Ste-Marie, C., E.A. Nelson, A. Dabros, and M.E. Bonneau, 2011:** Assisted migration: introduction to a multifaceted concept. *Forestry Chronicle*, **87(6)**, 724-730.
- Steenberg, J.W.N., P.N. Duinker, and P.G. Bush, 2011:** Exploring adaptation to climate change in the forests of central Nova Scotia, Canada. *Forest Ecology and Management*, **262(12)**, 2316-2327.
- Steffen, W., A. Persson, L. Deutsch, J. Zalasiewicz, M. Williams, K. Richardson, C. Crumley, P. Crutzen, C. Folke, L. Gordon, M. Molina, V. Ramanathan, J. Rockstrom, M. Scheffer, H.J. Schellnhuber, and U. Svedin, 2011:** The Anthropocene: from global change to planetary stewardship. *Ambio*, **40(7)**, 739-761.
- Steffensen, J.P., K.K. Andersen, M. Bigler, H.B. Clausen, D. Dahl-Jensen, H. Fischer, K. Goto-Azuma, M. Hansson, S.J. Johnsen, J. Jouzel, V. Masson-Delmotte, T. Popp, S.O. Rasmussen, R. Rothlisberger, U. Ruth, B. Stauffer, M.L. Siggaard-Andersen, A.E. Sveinbjörnsdóttir, A. Svensson, and J.W.C. White, 2008:** High-resolution Greenland Ice Core data show abrupt climate change happens in few years. *Science*, **321(5889)**, 680-684.
- Stern, N., 2006:** *The Economics of Climate Change*. Cambridge University Press, Cambridge, UK, 712 pp.
- Stevens, C.J., C. Dupre, E. Dorland, C. Gaudnik, D.J.G. Gowing, A. Bleeker, M. Diekmann, D. Alard, R. Bobbink, D. Fowler, E. Corcket, J.O. Mountford, V. Vandvik, P.A. Aarrestad, S. Muller, and N.B. Dise, 2010:** Nitrogen deposition threatens species richness of grasslands across Europe. *Environmental Pollution*, **158(9)**, 2940-2945.
- Stevens, V.M., C. Turlure, and M. Baguette, 2010:** A meta-analysis of dispersal in butterflies. *Biological Reviews*, **85(3)**, 625-642.
- Stewart, I.T., 2009:** Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes*, **23(1)**, 78-94.
- Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2005:** Changes toward earlier streamflow timing across western North America. *Journal of Climate*, **18(8)**, 1136-1155.
- Stewart, J.B., 1988:** Modelling surface conductance of pine forest. *Agricultural and Forest Meteorology*, **43**, 19-35.
- Stinson, G., W.A. Kurz, C.E. Smyth, E.T. Neilson, C.C. Dymond, J.M. Metsaranta, C. Goisvenue, C.J. Rampley, Q. Li, T.M. White, and D. Blain, 2011:** An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Global Change Biology*, **17(6)**, 2227-2244.
- Stirling, I. and A.E. Derocher, 2012:** Effects of climate warming on polar bears: a review of the evidence. *Global Change Biology*, **18(9)**, 2694-2706.
- Stow, D., A. Petersen, A. Hope, R. Engstrom, and L. Coulter, 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.
- Straille, D., R. Adrian, and D.E. Schindler, 2012:** Uniform temperature dependency in the phenology of a keystone herbivore in lakes of the Northern Hemisphere. *PLoS One*, **7(10)**, e45497, doi:10.1371/journal.pone.0045497.
- Strayer, D.L. and D. Dudgeon, 2010:** Freshwater biodiversity conservation: recent progress and future challenges. *Journal of the North American Benthological Society*, **29(1)**, 344-358.
- Sturm, M., J. Schimel, G. Michaelson, J.M. Welker, S.F. Oberbauer, G.E. Liston, J. Fahnestock, and V.E. Romanovsky, 2005:** Winter biological processes could help convert arctic tundra to shrubland. *BioScience*, **55(1)**, 17-26.
- Suarez, F., D. Binkley, M.W. Kaye, and R. Stottlemeyer, 1999:** Expansion of forest stands into tundra in the Noatak National Preserve, northwest Alaska. *Ecoscience*, **6(3)**, 465-470.
- Suggitt, A.J., C. Stefanescu, F. Paramo, T. Oliver, B.J. Anderson, J.K. Hill, D.B. Roy, T. Brereton, and C.D. Thomas, 2012:** Habitat associations of species show consistent but weak responses to climate. *Biology Letters*, **8(4)**, 590-593.
- Sunday, J.M., A.E. Bates, and N.K. Dulvy, 2012:** Thermal tolerance and the global redistribution of animals. *Nature Climate Change*, **2(9)**, 686-690.
- Suttle, K.B., M.A. Thomsen, and M.E. Power, 2007:** Species interactions reverse grassland responses to changing climate. *Science*, **315(5812)**, 640-642.
- Swab, R.M., H.M. Regan, D.A. Keith, T.J. Regan, and M.K.J. Ooi, 2012:** Niche models tell half the story: spatial context and life-history traits influence species responses to global change. *Journal of Biogeography*, **39(7)**, 1266-1277.
- Syvitski, J.P.M., A.J. Kettner, I. Overeem, E.W.H. Hutton, M.T. Hannon, G.R. Brakenridge, J. Day, C. Vorosmarty, Y. Saito, L. Giosan, and R.J. Nicholls, 2009:** Sinking deltas due to human activities. *Nature Geoscience*, **2(10)**, 681-686.
- Szabo, J.K., N. Khwaja, S.T. Garnett, and S.H.M. Butchart, 2012:** Global patterns and drivers of avian extinctions at the species and subspecies level. *PLoS One*, **7(10)**, e47080, doi:10.1371/journal.pone.0047080.
- Szeicz, J.M. and G.M. Macdonald, 1995:** Recent white spruce dynamics at the subarctic alpine treeline of north-western Canada. *Journal of Ecology*, **83(5)**, 873-885.
- Tarnocai, C., J.G. Canadell, E.A.G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov, 2009:** Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*, **23(2)**, GB2023, doi:10.1029/2008GB003327.
- Taylor, S., L. Kumar, N. Reid, and D.J. Kriticos, 2012:** Climate change and the potential distribution of an invasive shrub, *Lantana camara* L. *PLoS One*, **7(4)**, e35565. doi:10.1371/journal.pone.0035565.
- Tchebakova, N.M., E. Parfenova, and A.J. Soja, 2009:** The effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate. *Environmental Research Letters*, **4(4)**, 045013, doi:10.1088/1748-9326/4/4/045013.
- TEEB, 2009:** *TEEB Climate Issues Update. The Economics of Ecosystems and Biodiversity (TEEB)*. Hosted by the United Nations Environment Programme (UNEP), UNEP TEEB, Geneva, Switzerland, 32 pp.
- Teixiera, E., G. Fischer, H. van Veldhuizen, R. van Dingenen, F. Dentener, G. Mills, C. Walter, and F. Ewert, 2011:** Limited potential of crop management for mitigating surface impacts on global food supply. *Atmospheric Environment*, **45(15)**, 2569-2576.
- Telwala, Y., B.W. Brook, K. Manish, and M.K. Pandit, 2013:** Climate-induced elevational range shifts and increase in plant species richness in the Himalayan biodiversity epicentre. *PLoS One*, **8(2)**, e57103, doi:10.1371/journal.pone.0057103.
- ten Brink, P., A. Chiabai, M. Rayment, N. Braeuer, N. Peralta Bezerra, M. Kettunen, and L. Braat, 2008:** The cost of policy inaction – in monetary terms. In: *The Cost of Policy Inaction. The Case of Not Meeting the 2010 Biodiversity Target* [Braat, L.L. and P. ten Brink (eds.)]. Alterra-rapport 1718, Alterra, Wageningen University and Research and Institute for European Environmental Policy, Cereales Publishers, Wageningen, Netherlands, pp. 169-224.
- Terrier, A., M.P. Girardin, C. Perié, P. Legendre, and Y. Bergeron, 2013:** Potential changes in forest composition could reduce impacts of climate change on boreal wildfires. *Ecological Applications*, **23(1)**, 21-35.
- Teuling, A.J., M. Hirschi, A. Ohmura, M. Wild, M. Reichstein, P. Ciais, N. Buchmann, C. Ammann, L. Montagnani, A.D. Richardson, G. Wohlfahrt, and S.I. Seneviratne, 2009:** A regional perspective on trends in continental evaporation. *Geophysical Research Letters*, **36(2)**, L02404, doi:10.1029/2008GL036584.
- Thackeray, S.J., T.H. Sparks, M. Frederiksen, S. Burthe, P.J. Bacon, J.R. Bell, M.S. Botham, T.M. Brereton, P.W. Bright, L. Carvalho, T. Clutton-Brock, A. Dawson, M. Edwards, I.D. Jones, J.T. Jones, D.I. Leech, D.B. Roy, W.A. Scott, M. Smith, R.J. Smithers, I.J. Winfield, and S. Wanless, 2010:** Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology*, **16(12)**, 3304-3313.

- Thaxter**, C.B., A.C. Joys, R.D. Gregory, S.R. Baillie, and D.G. Noble, 2010: Hypotheses to explain patterns of population change among breeding bird species in England. *Biological Conservation*, **143**(9), 2006-2019.
- The Royal Society**, 2008: *Ground-level Ozone in the 21st Century: Future Trends, Impacts and Policy Implications*. Science Policy Series Report 15/08, London, UK, 132 pp.
- Thomas**, C.D., A.M.A. Franco, and J.K. Hill, 2006: Range retractions and extinction in the face of climate warming. *Trends in Ecology & Evolution*, **21**(8), 415-416.
- Thomas**, C.D., P.K. Gillingham, R.B. Bradbury, D.B. Roy, B.J. Anderson, J.M. Baxter, N.A.D. Bourn, H.Q.P. Crick, R.A. Findon, R. Fox, J.A. Hodgson, A.R. Holt, M.D. Morecroft, N.J. O'Hanlon, T.H. Oliver, J.W. Pearce-Higgins, D.A. Procter, J.A. Thomas, K.J. Walker, C.A. Walmsley, R.J. Wilson, and J.K. Hill, 2012: Protected areas facilitate species' range expansions. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(35), 14063-14068.
- Thomas**, J.A., D.J. Simcox, and R.T. Clarke, 2009: Successful conservation of a threatened *Maculinea* butterfly. *Science*, **325**(5936), 80-83.
- Thompson**, P.L., M.C. Jacques, and R.D. Vinebrooke, 2008: Impacts of climate warming and nitrogen deposition on alpine plankton in lake and pond habitats: an in vitro experiment. *Arctic Antarctic and Alpine Research*, **40**(1), 192-198.
- Thornick**, K., S. Venevsky, S. Sitch, and W. Cramer, 2001: The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model. *Global Ecology and Biogeography*, **10**, 661-667.
- Thornton**, P.K., J. van de Steeg, A. Notenbaert, and M. Herrero, 2009: The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. *Agricultural Systems*, **101**(3), 113-127.
- Thorup**, K., A.P. Tøttrup, and C. Rahbek, 2007: Patterns of phenological changes in migratory birds. *Oecologia*, **151**(4), 697-703.
- Throop**, H.L. and S.R. Archer, 2008: Shrub (*Prosopis velutina*) encroachment in a semidesert grassland: spatial-temporal changes in soil organic carbon and nitrogen pools. *Global Change Biology*, **14**(10), 2420-2431.
- Thuiller**, W., S. Lavorel, M.B. Araujo, M.T. Sykes, and I.C. Prentice, 2005: Climate change threats to plant diversity in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, **102**(23), 8245-8250.
- Tian**, H.D., L.C. Stige, B. Cazelles, K.L. Kausrud, R. Svarverud, N.C. Stenseth, and Z.B. Zhang, 2011: Reconstruction of a 1,910-y-long locust series reveals consistent associations with climate fluctuations in China. *Proceedings of the National Academy of Sciences of the United States of America*, **108**(35), 14521-14526.
- Tilman**, D., C. Balzer, J. Hill, and B.L. Befort, 2011: Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **108**(50), 20260-20264.
- Tingley**, M.W., M.S. Koo, C. Moritz, A.C. Rush, and S.R. Beissinger, 2012: The push and pull of climate change causes heterogeneous shifts in avian elevational ranges. *Global Change Biology*, **18**(11), 3279-3290.
- Tirado**, M.C., M.J. Cohen, N. Aberman, J. Meerman, and B. Thompson, 2010: Addressing the challenges of climate change and biofuel production for food and nutrition security. *Food Research International*, **43**(7), 1729-1744.
- Tisseuil**, C., M. Vrac, G. Grenouillet, A.J. Wade, M. Gevrey, T. Oberdorff, J.B. Grodwohl, and S. Lek, 2012: Strengthening the link between climate, hydrological and species distribution modeling to assess the impacts of climate change on freshwater biodiversity. *Science of the Total Environment*, **424**, 193-201.
- Tng**, D.Y.P., B.P. Murphy, E. Weber, G. Sanders, G.J. Williamson, J. Kemp, and D.M.J.S. Bowman, 2012: Humid tropical rain forest has expanded into eucalypt forest and savanna over the last 50 years. *Ecology and Evolution*, **2**(1), 34-45.
- Tockner**, K., S.E. Bunn, C. Gordon, R.J. Naiman, G.P. Quinn, and J.A. Stanford, 2008: Floodplains: critically threatened ecosystems. In: *Aquatic Ecosystems. Trends and Global Prospects*. [Polunin, N.V.C. (ed.)]. Cambridge Press, Cambridge, UK, pp. 45-61.
- Tomppo**, E., T. Gschwantner, M. Lawrence, and R.E. McRoberts (eds.), 2010: *National Forest Inventories – Pathways for Common Reporting*. Springer, New York, NY, USA, 612 pp.
- Trail**, L.W., C.J.A. Bradshaw, S. Delean, and B.W. Brook, 2010: Wetland conservation and sustainable use under global change: a tropical Australian case study using magpie geese. *Ecography*, **33**(5), 818-825.
- Trathan**, P.N., P.T. Fretwell, and B. Stonehouse, 2011: First recorded loss of an emperor penguin colony in the recent period of Antarctic regional warming: implications for other colonies. *PLoS One*, **6**(2), e14738, doi:10.1371/journal.pone.0014738.
- Trivedi**, M.R., P.M. Berry, M.D. Morecroft, and T.P. Dawson, 2008: Spatial scale affects bioclimate model projections of climate change impacts on mountain plants. *Global Change Biology*, **14**(5), 1089-1103.
- Tseng**, W.C. and C.C. Chen, 2008: Valuing the potential economic impact of climate change on the Taiwan trout. *Ecological Economics*, **65**(2), 282-291.
- Tsoutsos**, T., N. Frantzeskaki, and V. Gekas, 2005: Environmental impacts from the solar energy technologies. *Energy Policy*, **33**(3), 289-296.
- Tubby**, K.V. and J.F. Webber, 2010: Pests and diseases threatening urban trees under a changing climate. *Forestry*, **83**(4), 451-459.
- Turetsky**, M.R., E.S. Kane, J.W. Harden, R.D. Ottmar, K.L. Manies, E. Hoy, and E.S. Kasischke, 2011: Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. *Nature Geoscience*, **4**(1), 27-31.
- Turner**, W.R., B.A. Bradley, L.D. Estes, D.G. Hole, M. Oppenheimer, and D.S. Wilcove, 2010: Climate change: helping nature survive the human response. *Conservation Letters*, **3**(5), 304-312.
- Tylianakis**, J.M., R.K. Didham, J. Bascompte, and D.A. Wardle, 2008: Global change and species interactions in terrestrial ecosystems. *Ecology Letters*, **11**(12), 1351-1363.
- Uhl**, C. and J.B. Kauffman, 1990: Deforestation, fire susceptibility and potential tree responses to fire in the eastern Amazon. *Ecology*, **71**(2), 437-449.
- UN-HABITAT**, 2011: *Cities and Climate Change. Global Report on Human Settlements 2011*. Earthscan, London, UK and Washington DC, USA, 279 pp.
- UN DESA Population Division**, 2012: *World Urbanization Prospects, the 2011 Revision*. United Nations, Department of Economic and Social Affairs (UN DESA), Population Division, UN Publication, New York, NY, USA, 318 pp.
- Urabe**, J., J. Togari, and J.J. Elser, 2003: Stoichiometric impacts of increased carbon dioxide on a planktonic herbivore. *Global Change Biology*, **9**(6), 818-825.
- Urban**, M.C., M.A. Leibold, P. Amarasekare, L. De Meester, R. Gomulkiewicz, M.E. Hochberg, C.A. Klausmeier, N. Loeuille, C. de Mazancourt, J. Norberg, J.H. Pantel, S.Y. Strauss, M. Vellend, and M.J. Wade, 2008: The evolutionary ecology of metacommunities. *Trends in Ecology & Evolution*, **23**(6), 311-317.
- Urban**, M.C., J.J. Tewksbury, and K.S. Sheldon, 2012: On a collision course: competition and dispersal differences create no-analogue communities and cause extinctions during climate change. *Proceedings of the Royal Society B*, **279**(1735), 2072-2080.
- Uys**, R.G., J.W. Bond, and T.M. Everson, 2004: The effect of different fire regimes on plant diversity southern African grasslands. *Biological Conservation*, **118**(4), 489-499.
- Vadadi-Fulop**, C., C. Sipkay, G. Meszaros, and L. Hufnagel, 2012: Climate change and freshwater zooplankton: what does it boil down to? *Aquatic Ecology*, **46**(4), 501-519.
- Valdes**, P., 2011: Built for stability. *Nature Geoscience*, **4**(7), 414-416.
- van Asch**, M. and M.E. Visser, 2007: Phenology of forest caterpillars and their host trees: the importance of synchrony. *Annual Review of Entomology*, **52**, 37-55.
- van Asch**, M., P.H. Tienderen, L.J.M. Holleman, and M.E. Visser, 2007: Predicting adaptation of phenology in response to climate change, an insect herbivore example. *Global Change Biology*, **13**(8), 1596-1604.
- van Asch**, M., L. Salis, L.J.M. Holleman, B. van Lith, and M.E. Visser, 2012: Evolutionary response of the egg hatching date of a herbivorous insect under climate change. *Nature Climate Change*, **3**, 244-248.
- Van Auken**, O.W., 2009: Causes and consequences of woody plant encroachment into western North American grasslands. *Journal of Environmental Management*, **90**(10), 2931-2942.
- van de Waal**, D.B., A.M. Verschoor, J.M.H. Verspagen, E. van Donk, and J. Huisman, 2010: Climate-driven changes in the ecological stoichiometry of aquatic ecosystems. *Frontiers in Ecology and the Environment*, **8**(3), 145-152.
- van der Linde**, J.A., D.L. Six, M.J. Wingfield, and J. Roux, 2011: *Lasiodiplodia* species associated with dying *Euphorbia ingens* in South Africa. *Southern Forests: a Journal of Forest Science*, **73**(3-4), 165-173.
- van der Molen**, M.K., B.J.J.M. van den Hurk, and W. Hazeleger, 2011: A dampened land use change climate response towards the tropics. *Climate Dynamics*, **37**(9-10), 2035-2043.
- van der Werf**, G.R., J.T. Randerson, L. Giglio, G.J. Collatz, M. Mu, P.S. Kasibhatla, D.C. Morton, R.S. DeFries, Y. Jin, and T.T. van Leeuwen, 2010: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009). *Atmospheric Chemistry and Physics*, **223**, 11707-11735.
- Van Herk**, I.G., S.T. Gower, D.R. Bronson, and M.S. Tanner, 2011: Effects of climate warming on canopy water dynamics of a boreal black spruce plantation. *Canadian Journal of Forest Research / Revue Canadienne De Recherche Forestiere*, **41**(2), 217-227.

- van Kleunen, M., E. Weber, and M. Fischer, 2010: A meta-analysis of trait differences between invasive and non-invasive plant species. *Ecology Letters*, **13**(2), 235-245.
- van Mantgem, P.J., N.L. Stephenson, J.C. Byrne, L.D. Daniels, J.F. Franklin, P.Z. Fule, M.E. Harmon, A.J. Larson, J.M. Smith, A.H. Taylor, and T.T. Veblen, 2009: Widespread increase of tree mortality rates in the western United States. *Science*, **323**(5913), 521-524.
- Van Minnen, J.G., B.J. Strengers, B. Eickhout, R.J. Swart, and R. Leemans, 2008: Quantifying the effectiveness of climate change mitigation through forest plantations and carbon sequestration with an integrated land-use model. *Carbon Balance and Management*, **3**(1), 3, doi:10.1186/1750-0680-3-3.
- van Vliet, M.T.H., F. Ludwig, J.J.G. Zwolsman, G.P. Weedon, and P. Kabat, 2011: Global river temperatures and sensitivity to atmospheric warming and changes in river flow. *Water Resources Research*, **47**(2), W02544, doi:10.1029/2010WR009198.
- van Vuuren, D.P., M.G.J. den Elzen, P.L. Lucas, B. Eickhout, B.J. Strengers, B. van Ruijven, S. Wonink, and R. van Houdt, 2007: Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change*, **81**, 119-159.
- van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, N. Nakicenovic, S.J. Smith, and S.K. Rose, 2011: The representative concentration pathways: an overview. *Climatic Change*, **109**, 5-31.
- van Wilgen, B.W. and D.M. Richardson, 2012: Three centuries of managing introduced conifers in South Africa: benefits, impacts, changing perceptions and conflict resolution. *Journal of Environmental Management*, **106**, 56-68.
- Vaughan, N.E. and T.M. Lenton, 2011: A review of climate geoengineering proposals. *Climatic Change*, **109**(3-4), 745-790.
- Vedder, O., S. Bouwhuis, and B.C. Sheldon, 2013: Quantitative assessment of the importance of phenotypic plasticity in adaptation to climate change in wild bird populations. *PLoS Biol*, **11**(7), e1001605, doi:10.1371/journal.pbio.1001605.
- Veldman, J.W. and F.E. Putz, 2011: Grass-dominated vegetation, not species-diverse natural savanna, replaces degraded tropical forests on the southern edge of the Amazon Basin. *Biological Conservation*, **144**(5), 1419-1429.
- Vennetier, M. and C. Ripert, 2010: Climate change impact on vegetation: lessons from an exceptionally hot and dry decade in south-eastern France. In: *Climate Change and Variability* [Simard, S. (ed.)]. InTech Open, Rijeka, Croatia, pp. 225-242.
- Verburg, P., R.E. Hecky, and H. Kling, 2003: Ecological consequences of a century of warming in Lake Tanganyika. *Science*, **301**(5632), 505-507.
- Vieira, G., J. Bockheim, M. Guglielmin, M. Balks, A.A. Abramov, J. Boelhouwers, N. Cannone, L. Ganzert, D.A. Gilichinsky, S. Gotyachkin, J. Lopez-Martinez, I. Meiklejohn, R. Raffi, M. Ramos, C. Schaefer, E. Serrano, F. Simas, R. Sletten, and D. Wagner, 2010: Thermal state of permafrost and active-layer monitoring in the Antarctic: advances during the International Polar Year 2007-2009. *Permafrost and Periglacial Processes*, **21**(2), 182-197.
- Viglizzo, E.F., F.C. Frank, L.V. Carreno, E.G. Jobbagy, H. Pereyra, J. Clatt, D. Pincen, and M.F. Ricard, 2011: Ecological and environmental footprint of 50 years of agricultural expansion in Argentina. *Global Change Biology*, **17**(2), 959-973.
- Vilà-Cabrera, A., J. Martínez-Vilalta, L. Galiano, and J. Retana, 2013: Patterns of forest decline and regeneration across Scots pine populations. *Ecosystems*, **16**, 323-335.
- Vinukollu, R.K., R. Meynadier, J. Sheffield, and E.F. Wood, 2011: Multi-model, multi-sensor estimates of global evapotranspiration: climatology, uncertainties and trends. *Hydrological Processes*, **5**, 3993-4010.
- Visser, M.E. and C. Both, 2005: Shifts in phenology due to global climate change: the need for a yardstick. *Proceedings of the Royal Society of London Series B*, **272**(1665), 2561-2569.
- Visser, M.E., L.J.M. Holleman, and S.P. Caro, 2009: Temperature has a causal effect on avian timing of reproduction. *Proceedings of the Royal Society B*, **276**(1665), 2323-2331.
- Vitt, P., K. Havens, and O. Hoegh-Guldberg, 2009: Assisted migration: part of an integrated conservation strategy. *Trends in Ecology & Evolution*, **24**(9), 473-474.
- Vitt, P., K. Havens, A.T. Kramer, D. Sollenberger, and E. Yates, 2010: Assisted migration of plants: changes in latitudes, changes in attitudes. *Biological Conservation*, **143**(1), 18-27.
- Volney, W.J.A. and R.A. Fleming, 2007: Spruce budworm (*Choristoneura* spp.) biotype reactions to forest and climate characteristics. *Global Change Biology*, **13**(8), 1630-1643.
- Vongraven, D. and E. Richardson, 2011: Biodiversity – status and trends of polar bears. In: *Arctic Report Card: Update for 2011* [Richter-Menge, J., M.O. Jeffries, and J.E. Overland (eds.)]. National Oceanic and Atmospheric Administration (NOAA) Arctic Research Program, Washington, DC, USA, pp. 75-78, www.arctic.noaa.gov/report11/ArcticReportCard_full_report.pdf.
- Vörösmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers, 2000: Global water resources: vulnerability from climate change and population growth. *Science*, **289**(5477), 284-288.
- Vörösmarty, C.J., P.B. McIntyre, M.O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S.E. Bunn, C.A. Sullivan, C.R. Liermann, and P.M. Davies, 2010: Global threats to human water security and river biodiversity. *Nature*, **467**, pp. 555-561, doi:10.1038/nature09440.
- Vredenburg, V.T., R.A. Knapp, T.S. Tunstall, and C.J. Briggs, 2010: Dynamics of an emerging disease drive large-scale amphibian population extinctions. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(21), 9689-9694.
- Wagner, C. and R. Adrian, 2009: Cyanobacteria dominance: quantifying the effects of climate change. *Limnology and Oceanography*, **54**(6), 2460-2468.
- Walker, B. and J.L. Langridge, 1997: Predicting savanna vegetation structure on the basis of plant available moisture (PAM) and plant available nutrients (PAN): a case study from Australia. *Journal of Biogeography*, **24**, 813-825.
- Walker, B. and D. Salt, 2006: *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Island Press, Washington, DC, USA, 174 pp.
- Walker, B., C.S. Holling, S.R. Carpenter, and A. Kinzig, 2004: Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society*, **9**(2), 5, www.ecologyandsociety.org/vol9/iss2/art5/.
- Walker, D.A., H.E. Epstein, M.K. Reynolds, P. Kuss, M.A. Kopecky, G.V. Frost, F.J.A. Daniels, M.O. Leibman, N.G. Moskalenko, G.V. Matyshak, O.V. Khitun, A.V. Khomutov, B.C. Forbes, U.S. Bhatt, A.N. Kade, C.M. Vonlanthen, and L. Tichy, 2012: Environment, vegetation and greenness (NDVI) along the North America and Eurasia Arctic transects. *Environmental Research Letters*, **7**(1), 015504, doi:10.1088/1748-9326/7/1/015504.
- Walker, M.W.C., R.D. Hollister, G.H.R. Henry, L.E. Ahlquist, J.M. Alatalo, M.S. Bret-Harte, M.P. Calef, T.V. Callaghan, A.B. Carroll, H.E. Epstein, I.S. Jonsdottir, J.A. Klein, B. Magnusson, U. Molau, S.F. Oberbauer, S.P. Rewa, C.H. Robinson, G.R. Shaver, K.N. Suding, C.C. Thompson, A. Tolvanen, O. Totland, P.L. Turner, C.E. Tweedie, P.J. Webber, and P.A. Wookey, 2006: Plant community responses to experimental warming across the tundra biome. *Proceedings of the National Academy of Sciences of the United States of America*, **103**(5), 1342-1346.
- Walter, J., K. Grant, C. Beierkuhnlein, J. Kreyling, M. Weber, and A. Jentsch, 2012: Increased rainfall variability reduces biomass and forage quality of temperate grassland largely independent of mowing frequency. *Agriculture Ecosystems & Environment*, **148**, 1-10.
- Walters, R.J., W.U. Blanckenhorn, and D. Berger, 2012: Forecasting extinction risk of ectotherms under climate warming: an evolutionary perspective. *Functional Ecology*, **26**(6), 1324-1338.
- Walther, G.-R., S. Berger, and M.T. Sykes, 2005: An ecological 'footprint' of climate change. *Proceedings of the Royal Society B*, **272**(1571), 1427-1432.
- Walther, G.-R., A. Roques, P.E. Hulme, M.T. Sykes, P. Pysek, I. Kuehn, M. Zobel, S. Bacher, Z. Botta-Dukat, H. Bugmann, B. Czucz, J. Dauber, T. Hickler, V. Jarosik, M. Kenis, S. Klotz, D. Minchin, M. Moora, W. Nentwig, J. Ott, V.E. Panov, B. Reineking, C. Robinet, V. Semchenko, W. Solarz, W. Thuiller, M. Vila, K. Vohland, and J. Settele, 2009: Alien species in a warmer world: risks and opportunities. *Trends in Ecology & Evolution*, **24**(12), 686-693.
- Wang, B., J. Huang, X. Yang, B. Zhang, and M. Liu, 2010: Estimation of biomass, net primary production and net ecosystem production of China's forests based on the 1999-2003 National Forest Inventory. *Scandinavian Journal of Forest Research*, **25**(6), 544-553.
- Wang, K., E.D. Dickinson, M. Wild, and S. Liang, 2010: Evidence for decadal variation in global terrestrial evapotranspiration between 1982 and 2002: 2. Results. *Journal of Geophysical Research: Atmospheres*, **115**(D20), D20113, doi:10.1029/2010JD013847.
- Wang, S., S. Kang, L. Zhang, and F. Li, 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.
- Ward, D., 2005: Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science*, **22**(2), 101-105.
- Wardle, P. and M.C. Coleman, 1992: Evidence for rising upper limits of four native New Zealand forest trees. *New Zealand Journal of Botany*, **30**(3), 303-314.

- Warren, R., J. Price, A. Fischlin, S.D. Santos, and G. Midgley, 2011: Increasing impacts of climate change upon ecosystems with increasing global mean temperature rise. *Climatic Change*, **106**(2), 141-177.
- Warren, R., J. VanDerWal, J. Price, J.A. Welbergen, I. Atkinson, J. Ramirez-Villegas, T.J. Osborn, A. Jarvis, L.P. Shoo, S.E. Williams, and J. Lowe, 2013: Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change*, **3**(7), 678-682.
- Watrin, J., A.M. Lezine, and C. Hely, 2009: Plant migration and plant communities at the time of the "green Sahara". *Comptes Rendus Geoscience*, **341**(8-9), 656-670.
- Wearn, O.R., D.C. Reuman, and R.M. Ewers, 2012: Extinction debt and windows of conservation opportunity in the Brazilian Amazon. *Science*, **337**(6091), 228-232.
- Webb, B.W. and F. Nobilis, 2007: Long-term changes in river temperature and the influence of climatic and hydrological factors. *Hydrological Sciences Journal / Journal Des Sciences Hydrologiques*, **52**(1), 74-85.
- Welp, L.R., J.T. Randerson, and H.P. Liu, 2007: The sensitivity of carbon fluxes to spring warming and summer drought depends on plant functional type in boreal forest ecosystems. *Agricultural and Forest Meteorology*, **147**(3-4), 172-185.
- Weng, E.S. and G.S. Zhou, 2006: Modeling distribution changes of vegetation in China under future climate change. *Environmental Modeling & Assessment*, **11**(1), 45-58.
- West, J., S.H. Julius, P. Kareiva, C. Enquist, J.J. Lawler, B. Petersen, A.E. Johnson, and M.R. Shaw, 2009: U.S. natural resources and climate change: concepts and approaches for management adaptation. *Environmental Management*, **44**(6), 1001-1021.
- West, J.S., J.A. Townsend, M. Stevens, and B.D.L. Fitt, 2012: Comparative biology of different plant pathogens to estimate effects of climate change on crop diseases in Europe. *European Journal of Plant Pathology*, **133**(1), 315-331.
- Westerling, A., H. Hidalgo, D. Cayan, and T. Swetnam, 2006: Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, **313**(5887), 940-943.
- Westley, F., P. Olsson, C. Folke, T. Homer-Dixon, H. Vredenburg, D. Looibach, J. Thompson, M. Nilsson, E. Lambin, J. Sendzimir, B. Banerjee, V. Galaz, and S. van der Leeuw, 2011: Tipping toward sustainability: emerging pathways of transformation. *Ambio*, **40**(7), 762-780.
- Weyhenmeyer, G.A., E. Jeppesen, R. Adrian, L. Arvola, T. Blenckner, T. Jankowski, E. Jennings, P. Noges, T. Noges, and D. Straile, 2007: Nitrate-depleted conditions on the increase in shallow northern European lakes. *Limnology and Oceanography*, **52**(4), 1346-1353.
- Weyhenmeyer, G.A., D.M. Livingstone, M. Meili, O. Jensen, B. Benson, and J.J. Magnuson, 2011: Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes. *Global Change Biology*, **17**(1), 268-275.
- White, C.R., J.A. Green, G.R. Martin, P.J. Butler, and D. Gremillet, 2013: Energetic constraints may limit the capacity of visually guided predators to respond to Arctic warming. *Journal of Zoology*, **289**(2), 119-126.
- White, M.A., K.M. de Beurs, K. Didan, D.W. Inouye, A.D. Richardson, O.P. Jensen, J. O'Keefe, G. Zhang, R.R. Nemani, W.J.D. van Leeuwen, J.F. Brown, A. de Wit, M. Schaepman, X.M. Lin, M. Dettinger, A.S. Bailey, J. Kimball, M.D. Schwartz, D.D. Baldocchi, J.T. Lee, and W.K. Lauenroth, 2009: Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982-2006. *Global Change Biology*, **15**(10), 2335-2359.
- Wickham, J.D., T.G. Wade, and K.H. Riitters, 2012: Empirical analysis of the influence of forest extent on annual and seasonal surface temperatures for the continental United States. *Global Ecology and Biogeography*, **22**(5), 620-629.
- Wiedner, C., J. Rucker, R. Bruggemann, and B. Nixdorf, 2007: Climate change affects timing and size of populations of an invasive cyanobacterium in temperate regions. *Oecologia*, **152**(3), 473-484.
- Wiegand, K., D. Ward, and D. Saltz, 2005: Multi-scale patterns and bush encroachment in an arid savanna with a shallow soil layer. *Journal of Vegetation Science*, **16**(3), 311-320.
- Wiens, J.A., N.E. Seavy, and D. Jongsomjit, 2011: Protected areas in climate space: what will the future bring? *Biological Conservation*, **144**(8), 2119-2125.
- Wigley, B.J., W.J. Bond, and M.T. Hoffman, 2009: Bush encroachment under three contrasting land-use practices in a mesic South African savanna. *African Journal of Ecology*, **47**(Suppl s1), 62-70.
- Wild, M., J. Grieser, and C. Schär, 2008: Combined surface solar brightening and increasing greenhouse effect support recent intensification of the global land-based hydrological circle. *Geophysical Research Letters*, **35**(17), L17706, doi:10.1029/2008GL034842.
- Wiley, M.J., D.W. Hyndman, B.C. Pijanowski, A.D. Kendall, C. Riseng, E.S. Rutherford, S.T. Cheng, M.L. Carlson, J.A. Tyler, R.J. Stevenson, P.J. Steen, P.L. Richards, P.W. Seelbach, J.M. Koches, and R.R. Rediske, 2010: A multi-modeling approach to evaluating climate and land use change impacts in a Great Lakes River Basin. *Hydrobiologia*, **657**(1), 243-262.
- Wilhelm, S. and R. Adrian, 2008: Impact of summer warming on the thermal characteristics of a polymictic lake and consequences for oxygen, nutrients and phytoplankton. *Freshwater Biology*, **53**(2), 226-237.
- Wilkinson, S. and W.J. Davies, 2010: Drought, ozone, ABA and ethylene: new insights from cell to plant to community. *Plant Cell and Environment*, **33**(4), 510-525.
- Williams, A.L., K.E. Wills, J.K. Janes, J.K.V. Schoor, P.C.D. Newton, and M.J. Hovenden, 2007: Warming and free-air CO₂ enrichment alter demographics in four co-occurring grassland species. *New Phytologist*, **176**(2), 365-374.
- Williams, A.P., C.D. Allen, C.I. Millar, T.W. Swetnam, J. Michaelsen, C.J. Still, and S.W. Leavitt, 2010: Forest responses to increasing aridity and warmth in the southwestern United States. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(50), 21289-21294.
- Williams, A.P., C.D. Allen, A.K. Macalady, D. Griffin, C.A. Woodhouse, D.M. Meko, T.W. Swetnam, S.A. Rauscher, R. Seager, H.D. Grissino-Mayer, J.S. Dean, E.R. Cook, C. Gangogadagamage, M. Cai, and N.G. McDowell, 2013: Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, **3**, 292-297.
- Williams, J.W. and S.T. Jackson, 2007: Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment*, **5**(9), 475-482.
- Williams, J.W., S.T. Jackson, and J. E. Kutzbach, 2007: Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences of the United States of America*, **104**(14), 5738-5742.
- Williams, J.W., B. Shuman, and P.J. Bartlein, 2009: Rapid responses of the prairie-forest ecotone to early Holocene aridity in mid-continental North America. *Global and Planetary Change*, **66**(3-4), 195-207.
- Williams, J.W., B. Shuman, P.J. Bartlein, N.S. Diffenbaugh, and T. Webb, 2010: Rapid, time-transgressive, and variable responses to early Holocene midcontinental drying in North America. *Geology*, **38**(2), 135-138.
- Williams, J.W., J.L. Blois, and B.N. Shuman, 2011: Extrinsic and intrinsic forcing of abrupt ecological change: case studies from the late Quaternary. *Journal of Ecology*, **99**(3), 664-677.
- Willis, C.G., B.R. Ruhfel, R.B. Primack, A.J. Miller-Rushing, J.B. Losos, and C.C. Davis, 2010: Favorable climate change response explains non-native species' success in Thoreau's Woods. *PLoS One*, **5**(1), e8878, doi:10.1371/journal.pone.0008878.
- Willis, C.K.R., R.M.R. Barclay, J.G. Boyles, R.M. Brigham, V. Brack Jr, D.L. Waldien, and J. Reichard, 2010: Bats are not birds and other problems with Sovacool's (2009) analysis of animal fatalities due to electricity generation. *Energy Policy*, **38**, 2067-2069.
- Willis, K.J. and S.A. Bhagwat, 2009: Biodiversity and climate change. *Science*, **326**(5954), 806-807.
- Willis, K.J. and G.M. MacDonald, 2011: Long-term ecological records and their relevance to climate change predictions for a warmer world. *Annual Review of Ecology, Evolution, and Systematics*, **42**, 267-287.
- Willis, K.J., K.D. Bennett, S.A. Bhagwat, and H.J.B. Birks, 2010: 4 °C and beyond: what did this mean for biodiversity in the past? *Systematics and Biodiversity*, **8**(1), 3-9.
- Willmer, P., 2012: Ecology: pollinator-plant synchrony tested by climate change. *Current Biology*, **22**(4), R131-R132.
- Wilson, R., R. D'Arrigo, B. Buckley, U. Büntgen, J. Esper, D. Frank, B. Luckman, S. Payette, R. Vose, and D. Youngblut, 2007: A matter of divergence: tracking recent warming at hemispheric scales using tree ring data. *Journal of Geophysical Research: Atmospheres*, **112**(D17), D17103, doi:10.1029/2006JD008318.
- Winder, M. and D.E. Schindler, 2004: Climatic effects on the phenology of lake processes. *Global Change Biology*, **10**(11), 1844-1856.
- Winder, M. and U. Sommer, 2012: Phytoplankton response to a changing climate. *Hydrobiologia*, **698**(1), 5-16.
- Winder, M., J.E. Reuter, and S.G. Schladow, 2009: Lake warming favours small-sized planktonic diatom species. *Proceedings of the Royal Society B*, **276**(1656), 427-435.
- Winder, M., A.D. Jassby, and R. Mac Nally, 2011: Synergies between climate anomalies and hydrological modifications facilitate estuarine biotic invasions. *Ecology Letters*, **14**(8), 749-757.
- Winder, R., E.A. Nelson, and T. Beardmore, 2011: Ecological implications for assisted migration in Canadian forests. *Forestry Chronicle*, **87**(6), 731-744.

- Wing**, S.L. and E.D. Currano, 2013: Plant response to a global greenhouse event 56 million years ago. *American Journal of Botany*, **100**(7), 1234-1254.
- Wing**, S.L., G.J. Harrington, F.A. Smith, J.I. Bloch, D.M. Boyer, and K.H. Freeman, 2005: Transient floral change and rapid global warming at the Paleocene-Eocene boundary. *Science*, **310**(5750), 993-996.
- Winter**, M., O. Schweiger, S. Klotz, W. Nentwig, P. Andriopoulos, M. Arianoutsou, C. Basnou, P. Delipetrou, V. Didziulis, M. Hejda, P.E. Hulme, P.W. Lambdon, J. Pergl, P. Pyšek, D.B. Roy, and I. Kühn, 2009: Plant extinctions and introductions lead to phylogenetic and taxonomic homogenization of the European flora. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(51), 21721-21725.
- Wise**, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S.J. Smith, A. Janetos, and J. Edmonds, 2009: Implications of limiting CO₂ concentrations for land use and energy. *Science*, **324**(5931), 1183-1186.
- Witt**, G.B., R.A. Harrington, and M.J. Page, 2009: Is 'vegetation thickening' occurring in Queensland's mulga lands – a 50-year aerial photographic analysis. *Australian Journal of Botany*, **57**(7), 572-582.
- Witte**, J.C., A.R. Douglass, A. da Silva, O. Torres, R. Levy, and B.N. Duncan, 2011: NASA A-Train and Terra observations of the 2010 Russian wildfires. *Atmospheric Chemistry and Physics*, **11**(17), 9287-9301.
- Wittig**, V.E., E.A. Ainsworth, and S.P. Long, 2007: To what extent do current and projected increases in surface ozone affect photosynthesis and stomatal conductance of trees? A meta-analytic review of the last 3 decades of experiments. *Plant, Cell & Environment*, **30**(9), 1150-1162.
- Wittig**, V.E., E.A. Ainsworth, S.L. Naidu, D.F. Karnosky, and S.P. Long, 2009: Quantifying the impact of current and future tropospheric ozone on tree biomass, growth physiology and biochemistry. *Global Change Biology*, **15**(2), 396-424.
- Woillez**, M.N., M. Kageyama, G. Krinner, N. de Noblet-Ducoudre, N. Viovy, and M. Mancip, 2011: Impact of CO₂ and climate on the Last Glacial Maximum vegetation: results from the ORCHIDEE/IPSL models. *Climate of the Past*, **7**(2), 557-577.
- Wolken**, J.M., T.N. Hollingsworth, T.S. Rupp, F.S. Chapin, S.F. Trainor, T.M. Barrett, P.F. Sullivan, A.D. McGuire, E.S. Euskirchen, P.E. Hennon, E.A. Beever, J.S. Conn, L.K. Crone, D.V. D'Amore, N. Fresco, T.A. Hanley, K. Kielland, J.J. Kruse, T. Patterson, E.A.G. Schuur, D.L. Verbyla, and J. Yarie, 2011: Evidence and implications of recent and projected climate change in Alaska's forest ecosystems. *Ecosphere*, **2**(11), 124, doi:10.1890/ES11-00288.1.
- Wolkovich**, E.M., B.I. Cook, J.M. Allen, T.M. Crimmins, J.L. Betancourt, S.E. Travers, S. Pau, J. Regetz, T.J. Davies, N.J.B. Kraft, T.R. Ault, K. Bolmgren, S.J. Mazer, G.J. McCabe, B.J. McGill, C. Parmesan, N. Salamin, M.D. Schwartz, and E.E. Cleland, 2012: Warming experiments underpredict plant phenological responses to climate change. *Nature*, **485**, 494-497.
- Wood**, T.E., M.A. Cavaleri, and S.C. Reed, 2012: Tropical forest carbon balance in a warmer world: a critical review spanning microbial- to ecosystem-scale processes. *Biological Reviews*, **87**(4), 912-927.
- Woodburne**, M.O., G.F. Gunnell, and R.K. Stucky, 2009: Climate directly influences Eocene mammal faunal dynamics in North America. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(32), 13399-13403.
- Wookey**, P.A., R. Aerts, R.D. Bardgett, F. Baptist, K.A. Brathen, J.H.C. Cornelissen, L. Gough, I.P. Hartley, D.W. Hopkins, S. Lavorel, and G.R. Shaver, 2009: Ecosystem feedbacks and cascade processes: understanding their role in the responses of arctic and alpine ecosystems to environmental change. *Global Change Biology*, **15**(5), 1153-1172.
- Worrall**, J.J., G.E. Rehfeldt, A. Hamann, E.H. Hogg, S.B. Marchetti, M. Michaelian, and L.K. Gray, 2013: Recent declines of *Populus tremuloides* in North America linked to climate. *Forest Ecology and Management*, **299**, 35-51.
- Wu**, C.Y. and J.M. Chen, 2013: Diverse responses of vegetation production to interannual summer drought in North America. *International Journal of Applied Earth Observation and Geoinformation*, **21**, 1-6.
- Wu**, X.B. and S.R. Archer, 2005: Scale-dependent influence of topography-based hydrologic features on patterns of woody plant encroachment in savanna landscapes. *Landscape Ecology*, **20**(6), 733-742.
- Wu**, Z., H. Zhang, C.M. Krause, and N.S. Cobb, 2010: Climate change and human activities: a case study in Xinjiang, China. *Climatic Change*, **99**(3-4), 457-472.
- Xenopoulos**, M.A., D.M. Lodge, J. Alcamo, M. Marker, K. Schulze, and D.P. Van Vuuren, 2005: Scenarios of freshwater fish extinctions from climate change and water withdrawal. *Global Change Biology*, **11**(10), 1557-1564.
- Xu**, L., R.B. Myneni, F.S. Chapin III, T.V. Callaghan, J.E. Pinzon, C.J. Tucker, Z. Zhu, J. Bi, P. Ciais, H. Tømmervik, E.S. Euskirchen, B.C. Forbes, S.L. Piao, B.T. Anderson, S. Ganguly, R.R. Nemani, S.J. Goetz, P.S.A. Beck, A.G. Bunn, C. Cao, and J.C. Stroeve, 2013: Temperature and vegetation seasonality diminishment over northern lands. *Nature Climate Change*, **3**, 581-586.
- Yasuda**, M., H. Daimaru, and S. Okitsu, 2007: Detection of alpine moor vegetation change by comparison of orthonized aerophotographs at different times. *Geographical Review of Japan*, **80**, 842-856.
- Yi**, S.H., M.K. Woo, and M.A. Arain, 2007: Impacts of peat and vegetation on permafrost degradation under climate warming. *Geophysical Research Letters*, **34**(16), L16504, doi:10.1029/2007GL030550.
- Yoshikawa**, S. and K. Sanga-Ngoie, 2011: Deforestation dynamics in Mato Grosso in the southern Brazilian Amazon using GIS and NOAA/AVHRR data. *International Journal of Remote Sensing*, **32**(2), 523-544.
- Yvon-Durocher**, G., J.M. Montoya, M. Trimmer, and G. Woodward, 2011: Warming alters the size spectrum and shifts the distribution of biomass in freshwater ecosystems. *Global Change Biology*, **17**(4), 1681-1694.
- Zarnetske**, P.L., D.K. Skelly, and M.C. Urban, 2012: Biotic multipliers of climate change. *Science*, **336**(6088), 1516-1518.
- Zavaleta**, E.S., M.R. Shaw, N.R. Chiariello, B.D. Thomas, E.E. Cleland, C.B. Field, and H.A. Mooney, 2003: Grassland responses to three years of elevated temperature, CO₂, precipitation, and N deposition. *Ecological Monographs*, **73**(4), 585-604.
- Zelazowski**, P., Y. Malhi, C. Huntingford, S. Stith, and J.B. Fisher, 2011: Changes in the potential distribution of humid tropical forests on a warmer planet. *Philosophical Transactions of the Royal Society A*, **369**(1934), 137-160.
- Zeng**, Z., S. Piao, X. Lin, G. Yin, S. Peng, P. Ciais, and R.B. Myneni, 2012: Global evapotranspiration over the past three decades: estimation based on the water balance equation combined with empirical models. *Environmental Research Letters*, **7**(1), 014026, doi:10.1088/1748-9326/7/1/014026.
- Zerebecki**, R.A. and C.J.B. Sorte, 2011: Temperature tolerance and stress proteins as mechanisms of invasive species success. *PLoS One*, **6**(4), e14806, doi:10.1371/journal.pone.0014806.
- Zhang**, H., Y. Li, and X. Gao, 2009: Potential impacts of land-use on climate variability and extremes. *Advances in Atmospheric Sciences*, **26**(5), 840-854.
- Zhang**, Y.Y., M. Fischer, V. Colot, and O. Bossdorf, 2013: Epigenetic variation creates potential for evolution of plant phenotypic plasticity. *New Phytologist*, **197**(1), 314-322.
- Zhao**, M. and S.W. Running, 2010: Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science*, **329**(5994), 940-943.
- Zhou**, G., C. Peng, Y. Li, S. Liu, Q. Zhang, X. Tang, J. Liu, J. Yan, D. Zhang, and G. Chu, 2013: A climate change-induced threat to the ecological resilience of a subtropical monsoon evergreen broad-leaved forest in Southern China. *Global Change Biology*, **19**, 1197-1210.
- Zhou**, Y.P., K.M. Xu, Y.C. Sud, and A.K. Betts, 2011: Recent trends of the tropical hydrological cycle inferred from Global Precipitation Climatology Project and International Satellite Cloud Climatology Project data. *Journal of Geophysical Research: Atmospheres*, **116**(D9), D09101, doi:10.1029/2010JD015197.
- Zhu**, K., C.W. Woodall, and J.S. Clark, 2012: Failure to migrate: lack of tree range expansion in response to climate change. *Global Change Biology*, **18**(3), 1042-1052.
- Zhu**, Z.L., Z.Q. Xiong, and G.X. Xing, 2005: Impacts of population growth and economic development on the nitrogen cycle in Asia. *Science in China Series C: Life Sciences*, **48**, 729-737.
- Zimmermann**, N.E., N.G. Yoccoz, T.C. Edwards, E.S. Meier, W. Thuiller, A. Guisan, D.R. Schmatz, and P.B. Pearman, 2009: Climatic extremes improve predictions of spatial patterns of tree species. *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 19723-19728.
- Zimov**, N.S., S.A. Zimov, A.E. Zimova, G.M. Zimova, V.I. Chuprynin, and F.S. Chapin, 2009: Carbon storage in permafrost and soils of the mammoth tundra-steppe biome: role in the global carbon budget. *Geophysical Research Letters*, **36**(2), L02502, doi:10.1029/2008GL036332.
- Zurell**, D., V. Grimm, E. Rossmannith, N. Zbinden, N.E. Zimmermann, and B. Schroder, 2012: Uncertainty in predictions of range dynamics: black grouse climbing the Swiss Alps. *Ecography*, **35**(7), 590-603.
- Zyryanova**, O.A., V. T. Yaborov, T. I. Tchikhacheva, T. Koike, K. Makoto, Y. Matsuura, F. Satoh, and V. I. Zyryanov, 2007: The structure and biodiversity after fire disturbance in *Larix gmelinii* (Rupr.) Rupr. forests, northeastern Asia. *Eurasian Journal of Forest Research*, **10**(1), 19-29.