Chapter 4. Terrestrial and Inland Water Systems

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Executive Summary

A number of lines of evidence, including direct observations and proxy indicators of past functioning, show that many (but not all) groups of organisms are changing significantly in the present era, in a way consistent with climate change. Life-cycle events associated with springtime events are occurring earlier in the year in many cases. In some cases the life cycles of plants, herbivores and predators in the same location are changing differently, so interdependent species may be less synchronised in time. Although previous evidence suggested a general lengthening of the growing season and increased productivity in the boreal forests, more recent evidence indicates that the lengthening may be slowing or even reversed in some locations. While most recorded changes are consistent with expectations from a generally warming climate, and in some cases can be linked to climatic factors with some confidence, formal attribution to the specifically anthropogenic part of climate variation has rarely been done. Hence the degree to which anthropogenic climate change contributes to the observed changes in the terrestrial biosphere remains hard to quantify with confidence.

Increased concentrations of tropospheric ozone have been shown to impact negatively on plant production. Theory, modelling evidence and some observational studies indicate that terrestrial systems influence climate through their role in determining the physical characteristics of the land surface as well as through biogeochemical cycles. The difference between forested and non-forested landscapes appears to be particularly important. In the tropics, loss of forest cover exerts a warming influence on local climates through decreased evapotranspiration, and widespread loss may reduce rainfall at local to regional scales. In high latitudes, forest loss exerts a cooling influence through increased surface albedo. Forest loss in any region contributes to climatic warming through greenhouse gas emissions.

4.1. The Findings of the Previous Assessment

The material assessed in this chapter was last assessed by the IPCC in 2007, principally in the Working Group II report chapters 3 (Freshwater resources and their management; Kundzewicz et al., 2007) and 4 (Ecosystems, their properties, goods and services; Fischlin et al., 2007). Together they found that ‘Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases’. Although circumstantial evidence was offered that anthropogenic climate change was a cause of the observed changes, it was not possible to attribute a relative proportion of the changes to this cause with any confidence. An important finding was that 20-30% of the plant and animal species that had been assessed to that time were considered likely to be at increased risk of extinction if the global average temperature increases exceeded 1.5-2.5°C. No timescale was associated with this finding. The report noted that vulnerability to climate change could be exacerbated by the presence of other stresses, such as pollution.

4.2. A Changing View of Ecosystem Change

Ecologists no longer view ecosystems as inherently unchanging unless perturbed by an externally originating disturbance (refs). A growing body of both theory (ref) and observation (ref) supports the emerging view that most ecosystems vary substantively over time in the relative magnitude of their components and fluxes, even under a relatively constant environment. Furthermore, attempts to restrict this intrinsic variation - or that resulting from imposed disturbances - are frequently futile, and may damaging the capacity of the ecosystem to adapt to changing environments (?Folke et al., 2004).

A related conceptual shift has been to view ecosystems as containing humans, rather than existing in a natural state that is altered by humans without any feedback to the human system (Gunderson & Holling, 2001). The emerging view is of relatively tightly coupled social-ecological systems, which means that their joint dynamics are governed not only by biophysical processes such as energy flows, material cycles, competition and predation, but by social processes such as economics, politics, culture and individual preferences (B. H. Walker & Salt, 2006).

4.2.1. Ecosystems as Dynamic and Adaptive Entities

This concept of ecosystems as dynamic rather than constant entities, along with the realisation that due to the reach and intensity of human activities few ecosystems can any longer be considered to be in an anthropogenically-unperturbed state, has led to increased focus on how ecosystems behave in the vicinity of their environmental limits, rather than solely on their behaviour in their inferred preferred state, near the middle of their domain (?Scheffer et al., 2009). The notion of thresholds has become a prominent ecological concern **[Reference to thresholds, eg Rockstrom planetary boundaries**]. Some of the thresholds that have been discussed reflect a human preference that the ecosystem stays within certain bounds. Others reflect fundamental biophysical properties, such as the melting point of ice, which determines (among other things) the occurrence of permafrost-based ecosystems. A third category of threshold reflects system dynamics: the point at which the net effect of all the positive and negative feedback effects that characterise ecosystems is positive, causing a perturbation to become accentuated and lead to a new ecosystem state, from which the system will not spontaneously return in the short term. The new state will typically exhibit different dynamics, mean composition, sensitivity to environmental drivers and flows of ecosystem services relative to the prior state. An ecosystem regime shift is said to have occurred.

The early detection and prediction of ecosystem thresholds, particularly of the third type, is an area of active research. There are indications (?Scheffer, 2009) that an increase in ecosystem variability signals the impending approach of a threshold, but in practice, such signals may not be detectable against background noise and uncertainty until it is too late to avoid the threshold (Biggs, Carpenter, & Brock, 2009).

The term ‘resilience’ has attracted a range of meanings in different disciplines. In ecology it is used both in the sense of ‘a measure of the ability of these systems to absorb changes of state variables, driving variables and parameters, and still persist’ (Holling, 1973), but also in a broader sense of being able to adapt to change, without necessarily remaining within the same dynamical range (B. Walker, Hollin, Carpenter, & Kinzig, 2004). One source of such adaptability is the process of evolution, which generates variability and then selects for those organisms better able to survive and reproduce in the given environment. Organisms also typically exhibit a degree of physiological or behavioural adaptability (phenological adaptation) that does not require genetic change. A less well-understood source of adaptation is the configuration and functional form of interactions within an ecosystem, that leads to new stable states (www.regimeshifts.org). Third occurs when the ecosystem contains human agents sufficiently powerful to alter the ecosystem regime, and particularly where learning and technological development are involved.

4.2.2. What the Paleoecological Record Can and Cannot Tell Us

Paleoclimatic observations and modeling indicate that the Earth's climate has always changed on a wide range of time-scales, and in many cases, has changed in ways that are well-understood, particularly those changes over the last million years (Jansen, J.T., & others, 2007; IPCC AR5 WGI Chapter 5). In contrast, independent paleoecological records demonstrate that the planet's biota, carbon cycle and associated feedbacks and services have responded to this climatic change, particularly when the climatic change was large (e.g., Claussen, 2009; Arneth et al., 2010; Dawson, Jackson, House, Prentice, & Mace, 2011). Excellent examples of past large climate change events that drove large ecoclogical change include events linked with the extinction of species: the Palaeocene-Eocene Thermal Maximum (PETM, 56 Ma; Wing et al., 2005; Jaramillo et al., 2010), the early Eocene Climatic Optimum (EECO, 53-50 Ma; Woodburne, Gunnell, & Stucky, 2009), the Pliocene (5.3 to 2.6 Ma; Haywood & Valdes, 2006; Haywood et al., 2011), and the Last Glacial Maximum (LGM) to Holocene transition (Clark et al., 2009; Gill, Williams, Jackson, Lininger, & Robinson, 2009; J. W. Williams, Shuman, Bartlein, Diffenbaugh, & Webb, 2010; Prentice, Harrison, & Bartlein, 2011). The paleoecological record thus confirms that large climate change yields large ecological change, but none of the well-studied past periods of large climate change involved rates of global climate change approaching the rapidity of change likely in the next century and beyond (Jansen, et al., 2007; IPCC AR5 Chapter 12). *Thus, the paleoecological record confirms that future global terrestrial ecosystem change will likely be large. However, this same record is insufficient to reveal the complexity of future change because the rates of future global climate change will likely be faster than any witnessed by the Earth's biota since the ateroid-driven mass extinction event at the Cretaceous-Paleogene boundary at ca. 65 Ma (Schulte et al., 2010).* **[Care with this, because of Younger Dryas - Subcontinential, but very fast. Another big difference is the interaction with other human drivers of ecosystem change: land use, over exploitation esp fisheries, etc.]**

[INSERT FIGURE 4-1 HERE
Possible Figure 4-1: To highlight the unprecedented nature of future climate change. Update/modify the figure (Stephen T. Jackson & Overpeck, 2000), to include the paleoclimatic events mentioned in text. Only focus on range of estimated global change – e.g., with box/wiskers. Color code them to indicate the extent to which extinctions or other ecological changes (e.g., large-scale biome shifts) were associated.]

The paleoecological record also serves to highlight that it is likely that most of the Earth's natural ecosystems and landscapes will be altered substantially by future climate change **[need to discuss whether emissions scenarios make much difference]** , just as most of the Earth's terrestrial ecosystems were altered as the globe warmed a comparible amount (ca. 5°C) in the past, although at a rate at least six times slower (Jansen, et al., 2007) than is likely in the future. Biomes will move, species mixtures will change, and some novel new plant communities will emerge in response to regional climatic conditions emerging that are unlike any on Earth today, or even in the past (J. W. Williams & Jackson, 2007; J. W. Williams, Jackson, & Kutzbacht, 2007; MacDonald, 2010; Prentice, et al., 2011) *evidence to the contrary, the paleoecological record indicates it is reasonable to assume that most natural terrestrial systems of the globe will be impacted if future climate change remains unchecked, and the magnitude of future global climate change reaches ca. 5°C above pre-industrial. In addition, the paleoecological record indicates that it will be difficult to maintain or restore many ecological systems in their current states (S. T. Jackson & Hobbs, 2009).*

The paleoecological record also reveals that radiative climate forcing even slower than that anticipated for the 21st century (IPCC AR5 Chapter 12) often drove surprisingly abrupt, or non-linear, regional change in terrestrial and aquatic systems. Examples are widespread, but include the response to glacial and deglacial, ice-sheet dominated climatic forcing (e.g., Harrison & Goni, 2010; J. W. Williams, Blois, & Shuman, 2011), as well as to slower orbitally-driven change during the most recent Holocene interglacial (e.g., Booth et al., 2005; Kropelin et al., 2008; J. W. Williams, et al., 2010; J. W. Williams, et al., 2011) - in all cases, specific periods of abrupt ecological response were regionally distinct in nature and were more time-transgressive for small, slow changes in forcing (e.g., during the Holocene) than for larger, more rapid changes. *It remains unclear whether state-of-the-art climate and Earth system models can simulate the full range of abrupt change observed in the past, and thus it is likely that there will be unanticipated abrupt changes in climate and associated ecosystem impacts in the future (IPCC AR5, Chapter 5).*

It has been demonstrated that state-of-the-art vegetation models are able to simulate the much of the biome-level equilibrium response of terrestial to large paleoclimate change (e.g. Prentice, et al., 2011), but much of the more complex, time-dependent change, particularly at regional scales has not been simulated. *The paleoecological record indicates that vegetation in many parts of the world has the potential to respond within years to a few decades to climate change (e.g., Watrin, Lezine, & Hely, 2009; J. W. Williams, Shuman, & Bartlein, 2009; A. D. Mueller et al., 2009;* Harrison & Goni, 2010*), and this same record thus provides a critical model evaluation opportunity that should be exploited to gain confidence in time-dependent simulations of future change, particularly given the complex role that interacting climate change and vegetation disturbance has played in the past (e.g., Marlon et al., 2009; S.T. Jackson, Gray, & Shuman, 2009; J. W. Williams, et al., 2009; Daniau, Harrison, & Bartlein, 2010).*

4.2.3. Landscapes and Social-Ecological Systems [and the Effect of Scale of Analysis and Management]

The responses of terrestrial and freshwater ecosystems to climate change are often shaped by their interaction with people across spatial and temporal scales. The harvest, conversion, and/or management of ecosystems by humans varies by culture, affluence, markets, policies, and by the biophysical features of the landscape, providing a complex backdrop against which ecosystem responses to climate change must be interpreted. The interactions among ecological, social, and economic systems are important for understanding both the observed and predicted responses of terrestrial and freshwater ecosystems to climate change, and the potential for management interventions that could mitigate these impacts.

[We decided to see how these issues are coming into othersections and then decide how to continue]

4.2.4. Multiple Stressors and the Role of Climate Change

4.2.4.1. Land Use Change (LUC)

Seventy eight publications since 2008 were reviewed for this analysis (Table 3-1). Two kinds of studies were distinguished: a) the analysis of historical data series; and b) model-based predictions. In both cases, the relationship between CC and LUC was hard to separate, since both changes generally occur at the same time. The studies were classified according to their geographical area (i.e. continent), as follows: global (15), Africa (8), Asia, 19), Europe (15), Latin America and Caribe (15), Oceania (1) and United States and Canada (11). Most them report warming . Changes in precipitation are more variable. Several studies report rainfall decreases (drying), desertification, and changes in rainfall pattern.

[INSERT TABLE 4-1 HERE
Reviewers need to download Excel file <WGIIAR5-Chap4_ZODtab4-1.xls> from ZOD site.]

[It would be good to make reference to the growing literature showing the dynamic interactions between land use and regional climate (e.g., changes in vegetation roughness, ET, albedo, etc. alter climate, which then in turn affects ecosystems). This may be covered in WG1, but it should be recast here in terms of impacts.]

The type of LUC differed greatly among continents. The replacement of native forests and grasslands by new agricultural and grazing areas largely prevailed in Africa, Asia and Latin America. These LUCs were either driven by population pressures, market or both. LUCs driven by national or supranational polices are prevalent in Europe, mostly leading to aforestation/reforestation and decreases in agricultural production.

The consequences of change were assessed by soil, hydrological and ecological indicators. Many studies reported the combined effects of climate and landuse change on soil organic carbon. Although soil organic carbon was often found to be increased by CO_2 fertilization, the magnitude of this effect ws always smaller than the decrease of soil organic carbon that would be caused by the associated warming. In Latin America, Africa and Asia soil organic carbon decreases were mainly driven by agricultural and grazing land conversion from forests and native vegetation. Conversion to soybean, maize and oil palm drove most agricultural landuse change in Latin America and Africa. Conservation agriculture and no till farming systems, covering 47 Mha in South America, prevented further soil erosion losses in these areas. Some studies report biodiversity losses by monoculture cropping, particularly in terms of species richness. Decreases in biodiversity range 35-74 % in the Congo and 60-77 % in Asia-Oceania. Only 18-45 % of the original biome coverage is expected to remain intact by 2100.

Land conversion to agriculture or agriculture intensification caused substantial hydrological impacts on ecosystems. Runoff and base flow increases were reported in Latin America and United States. Grazing intensification was found to increase soil water infiltration in African grasslands. Land use change is the main cause of change in groundwater recharge, sediment yield and lake levels in the United States. Warming was found to cause migration of species either to higher latitudes and altitudes, in combination with snow melting and disappearance of cryogenic areas and permafrost.

[RB]
Many of the CMIP5 Earth System Model projections include scenarios of anthropogenic land cover change, which are the dominant cause of large-scale vegetation change in the RCP scenarios. At the global scale, the effects of climate change on the global distribution of vegetation cover is secondary to land use change in these projections.

[INSERT FIGURE 4-2 HERE
Possible Figure 4-2: Zonal mean anthropogenic land use fraction in CMIP5 simulations [this is from the HadGEM2-ES Earth System Model as an illustration]

4.2.4.2. Use Pressure

Humans are placing increasing pressure on ecosystems, due to a combination of population growth and increasing consumption per capita . The capacity of ecosystems to continue to supply benefits to people (‘ecosystem services’) at the required level is seriously threatened (Proenca & Pereira, 2011). However, it is difficult to separate the effects of climate change from those of use pressure. For instance, an assessment of large-scale trends in net primary productivity (NPP) of grasslands and deciduous forest in central and eastern United States could not quantify the changes due to management and technology independently from climate effects (Twine & Kucharik, 2009). Air pollution, climate change and anthropogenic pressure related to expansion of urban areas have pronounced effects on the health and growth of forests (Bytnerowicz, Arbaugh, Fenn, Gimeno, & Paoletti, 2008).

Grassland yield in the Tibetan Plateau (China) region showed marked inter-annual fluctuation, but increasing temperature in the last 18 years is suggested to be the main cause of increased grassland yield. However, reduced grazing pressure and changes to the seasonal pattern of grazing could also have influenced the grassland yield trend (Fan et al. 2010). Warming and grazing did not affect seasonal average ecosystem respiration of alpine meadows in the Tibetan plateau. Warming significantly increased seasonal average soil respiration by 9.2%, and soil temperature explained 63-83% of seasonal ecosystem respiration variations and 19-34% of soil respiration variations.

Transformation to a market economy coupled with limited state assistance (often combined with climate change) was invoked as a main degradation factor in Mongolian pastoralism. This has decreased rural water supplies, reduced mobility, and increased overgrazing, leading to land degradation over the last 15 years (Sternberg, 2008).

In a simulation study, drought (2 years with 33% less precipitation) show a decrease in profits from pastoralism by up to 57%, but pastoral land use of the rangeland increased surface runoff by 20%, doubled infiltration, and thus enhanced water availability for down-stream irrigation agriculture (Freier, Schneider, & Finckh, 2011). In the Patagonian steppe, Paruelo et al. (2008) found the inter-annual variability of precipitation to be more important than the grazing regime in explaining differences in tussock density. (2009) found climate change and rapid socio-economic development to increase the dominant land cover types (grassland and barren), together with the homogeneity and fragmentation of the landscape in the semi-arid grasslands in Inner Mongolia.

(2011) the energy budgets of shortgrass steppe under three different grazing intensity treatments. Their study confirms that precipitation, not grazing treatment, explains the majority of variation in aboveground biomass. Variability of forage production was explained primarily by precipitation and soil moisture rather than grazing intensity.

Other ecosystem benefits, like recreation and tourism, can be affected by global climate change. These effects may be magnified if warmer and drier weather encourages more visitors for, or makes them more likely to participate in ecologically damaging activities at the coast in UK (Coombes & Jones, 2010).

Land use decisions will be affected by future changes in the climate, but also the feedbacks from land use change to the global climate system through greenhouse gas fluxes. Socio-economic and technological changes are likely to be the most important drivers for land use, with climate change having a smaller influence. (Rounsevell & Reay, 2009). Many of the key driving factors in southern African savannas are generated externally, such as economic globalisation and climate change (Eriksen & Watson, 2009). Global climate change, population increases, and rodent damage are invoked as causes of QTP rangeland degradation, but some Western observers claim that traditional pastoral practices were sustainable, and identify either previous or more recent state policies as the cause of degradation (Harris, 2010).

4.2.4.3. N Deposition

The global nitrogen cycle has been strongly perturbed by human activity over the past century (Gruber & Galloway, 2008, Galloway et al., 2008). Human activities are currently transferring 160 TgN/y from the atmosphere to the land and ocean, on top of a natural flux of about 255 TgN/y. The river-born flux from land to the coastal oceans has increased by 50 TgN/y above the natural 30 TgN/y. Many of the sources of additional reactive nitrogen share root causes with changes in the carbon cycle - such as increased use of fossil fuels and expansion and intensification of global agriculture. Thus in most regions the effects of increased nitrogen loading are additional to elevated CO2 , ozone, UV and climate change. The effects of long-term nitrogen deposition in excess of natural rates on biodiversity have been reviewed by (2010). The many experiments and observations are concentrated in temperate and boreal Europe and North America, but show a consistent pattern of increase in the dominance of a few nitrogen-loving species and loss of overall species richness at loads exceeding between 5 and 20 kgN/ha/y. The multiple mechanisms suggested to contribute to this pattern are described by (2010). Changes in the competitive balance within the plant community are particularly important (Harpole & Tilman, 2007). The strongest projected regional increase in nitrogen deposition – exceeding 30 kg N/ha/y by 2030 - is in South China and South-East Asia, where it coincides with an area of high biodiversity (Phoenix et al., 2006). Analyses using the multi-factor biodiversity change model Globio3 suggest that nitrogen deposition is a significant contributing factor to terrestrial biodiversity loss, but relatively much smaller than factors such as habitat loss due agricultural, settlement and infrastructural expansion and deforestation and forest degradation (TEEB, Leadley et al., 2010).

[Strengthen N and CC interactions discussion, i.e., N often limiting to CO2 and CC stimulation of plant growth. E.g., synergistic roles of N dep and CC /CO2 in boosting forest growth in many areas.]

4.2.4.4. Ozone

[PL: Mention that O3 damage suggested as possibly important to divergence problem in use of tree rings as temperature indicator]
[RB: from Stephen Sitch, Leeds University; not yet verified the statements some of this is copied direct from other material or paraphrased so needs a careful going through; the following 3 paragraphs are based on, or possibly even copied from, the UN hemispheric transport of air pollution (HTAP) – need to check and revise if needed]

The annual average ground-level O_3 mixing ratio averaged across North America, Europe, South Asia, and East Asia and the ensemble of participating models is ~37 parts per billion by volume (ppbv) (± 4 ppbv standard deviation).

Based on estimates in the literature, about 20–25% of this annual average ground-level concentration originates in the stratosphere and a similar fraction is formed from natural emissions of precursors. The remainder is due to anthropogenic sources of precursors from within the region itself and transported from outside the region. The relative contribution of anthropogenic and natural, regional and extra regional sources varies by location, season, and year.

O_3 causes damage to crops, forests, and grasslands, which has important implications for productivity, biodiversity, and food security and may be an important contributing factor to the agricultural yield gap that currently exists across much of Asia. Global yield losses of four staple crops due to exposure to O3 are estimated to be between 3%–16%, depending on the crop, and are valued at $14 billion to $26 billion per year. Based on the HTAP multi-model experiments, intercontinental transport may be responsible for 5% to 35% of the estimated crop yield losses depending on the location, crop and response function used, subject to large uncertainties.

Cumulative seasonal exposures greater than 40ppb are a threat to sensitive vegetation (The Royal Society, 2008). Ozone reduces plant growth, crop and forest yields (Ashmore, 2005). During the 1980s, losses in annual arable crop production in the US were **[estimated as??]** $2-4 billion. In 2000, EU losses were 6.7Billion Euro (Holland et al., 2006) **[why pick these specific dates? Are they representative, or outliers?]** In 2000, global yields reduced by $14-26 billion for rice, soybean, maize, and wheat combined (large variation: 2% maize – 16% soybean) (Van Dingenen et al., 2009); Yield losses also occurred for wheat and rice in South Asia, and wheat in Sub-Saharan Africa. These are based on N. American & European exposure-response relationships [check what this means].

However, experimental studies for India & Pakistan indicate yield losses at ambient ozone of 10% rice, 13-47% wheat, 20% Mung bean, 24% spinach, 30% Pea, 45% carrot. **[what does this imply – that losses would be even greater under higher than ambient ozone? Or just that losses occur anyway?]**

Projections for 2030 indicate increase losses for wheat & rice, little change for soybean & maize (Van Dingenen, et al., 2009). **[what scenario?]**

Biofuel crops, willow & poplar, are known to be sensitive to O3. This may need to be considered in assessments of the extent to which renewable energy sources could meet future energy demands **[cite IPCC SRREN – was it considered there?]**

A meta-analysis by xxxx showed a decrease in stomatal conductance with ozone exposure. However, there is some evidence that ozone directly effects conductance by interfering with plant signaling, e.g. grass species (Mills, Hayes, Wilkinson, & Davies, 2009). “Decreased growth and increased water use of mature forest trees under episodically high ambient O3 concentrations” (McLaughlin, Nosal, Wullschleger, & Sun, 2007) ”Canopy water use and empirically modeled streamflow patterns over a 23-yr observation period suggest that current ambient ozone exposures may exacerbate the frequency and level of negative effects of drought on forest growth and stream health.” (McLaughlin, Wullschleger, Sun, & Nosal, 2007). Hence in "ambient" ozone, with loss of stomatal functioning, stomata are more open than normal, transpire more, less river runoff. This is in contradiction to the Wittig et al., meta-analysis showing stomatal conductance decreases **[possibly as a result of an indirect reduction**

in demand for CO2 due to O3 damage to plant production (i.e. what we have in JULES; RB: Need to check what he means here].

The apparent contradiction in observations may be linked to: the level of O3 exposure (it appears "ambient" o3 level lead to impaired stomatal function, v. high levels to defoliation etc); changes in LAI, e.g. o3 damage leads to reduced photosynthesis, reduced leaf area, less evapo-transpiration. So it may be that under acute ozone that indirect effect dominates (also helped by enhanced leaf senescence), whereas chronic low levels, the direct effect dominates. In short there some pretty interesting uncertainty of O3 on the hydrological cycle..
[Not much litterature on O3 x CO2 interactions - but they could be very important. The Rhinelander CO2 x O3 FACE experiment has some great stuff (e.g., Hofmockel et al. 2011)]

4.2.4.5. Rising CO_2

Experimental investigation of the effects of elevated CO2 on plants and ecosystems has continued with increasingly realistic and longer duration treatments, leading to a re-evaluation of some of the quantitative conclusions based on earlier studies conducted in small chambers, and the models derived from them (Long et al 2006, challenged by Tubiello et al 2007 and rebutted by Ainsworth et al 2008). Leakey et al (2009) summarise insights derived from Free Air Circulation Experiments (FACE), considered the most realistic experimental approach, and conclude that despite partial down-regulation during long-term exposure, stimulation of photosynthetic carbon assimilation due to elevated CO2 persists at a level of 19 to 46% for 600 ppm CO2 relative to 370 ppm. Nitrogen use efficiency and water use efficiency are both increased under higher levels of CO2, as is dark respiration. Stable isotope studies also suggest a historical increase in intrinsic plant water use efficiency (ref), which may have influenced historical evapotranspiration, soil moisture and streamflows to some extent (?Gerten et al., 2008).

Production in plants with a C4 photosynthetic system (which includes most warm-area grasses, maize and sugar cane) responds to rising CO2 indirectly, through more efficient use of water, especially under drought circumstances. The long-term net outcome of direct and indirect processes on harvest yield in crop species is less than the increase in either photosynthesis or net primary production. Average observed yield responses in FACE experiments are 14 + 2% (+ 90 CI) for [CO2] around 600 ppm relative to around 370 ppm, whereas chamber-based experiments suggested 31 + 10%. **[Cross-chapter linkage with food security here. I think this text is best placed in our chapter but we need to check for consistency with the other chapter.]** (2007) review the combined effects of elevated CO2, temperature, nitrogen deposition and management on carbon sequestration in temperate and boreal forests and conclude that findings extrapolated from experiments that only consider one of these factors in isolation can be misleading. The issue of the effects of rising CO2 on carbon sequestration are dealt with more fully in chapter X of WG1

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 and as yet poorly predictable (Potvin et al., 2007). For example, in one ten-year temperate grassland experiment in Minnesota, elevated CO2 halved the loss of species richness due to nitrogen addition (?Reich, 2009), whereas no such change was reported for a similar experiment in annual grassland on serpentine soils in California (Shaw et al 2002, Zavaleta et al 2003) or an alpine grassland in France (Bloor et al 2010). Some of the mechanisms of community and production changes under multi-factor forcing may be mediated through changes in plant litter quality, although in the temperate grassland experiment described above the changes in litter decomposition rates were less marked than the changes in the chemical composition of tissues (?Knops, Naeemw, & Reich, 2007). **[Perhaps another important point is that many physiologically based models generate a very strong protective effect of CO2 on vegetation. There is growing concern that experiments don't always confirm this (e.g, Korner refs, World Bank work done on Amazon forest senstivity, etc.)]**

[Other general point – may be relevant to section on CO2 under 4.2.4 and/or FAQ on non-GHG effects of CO2]: There is a strong steer towards making WG2 relevant to Article 2 of the UNFCCC, ie: "Avoiding dangerous climate change" and "a time-frame sufficient to allow ecosystems to adapt naturally to climate change. Currently the former is couched in terms of global mean temperature rise (eg: 2°C). However for ecosystems in particular it may be considerably more complex than that – other related drivers (CO2, O3) may be important but may not relate very precisely to global mean temperature rise. There is a large uncertainty in climate sensitivity (ie: global warming for doubled CO2), so the inverse of this is that there is a large uncertainty in the CO2 concentration that would accompany any given level of global warming (such as 2°C). Different studies may assume different changes in (for example) CO2 concentration for a given level of warming – or at least may not fully represent the uncertainty in the relative changes in atmospheric composition and climate. I suggest producing a plot showing, for example, the estimated pdf of CO2 for (say) 2°C (Meinshousen has done such a plot – see below) and then overplotting on this the warming & CO2 rise assumed in key ecosystem impacts studies – to show how much of the uncertainty space is covered.

[INSERT FIGURE 4-3 HERE
Possible Figure 4-3: Probability of exceeding 2°C global warming for different CO2 concentration stabilisation level. Use this (or similar plot) to illustrate relationships between CO2 and warming assumed in ecosystem impacts studies – plot individual studies on this chart.]
[RB: I think I will plot global temperature vs. CO2 rise for the RCP projections, with estimated uncertainties, and then overplot the same quantities for individual ecosystem studies to show how the "climate-CO2" space covered by ecosystem studies overlaps with the "climate-CO2" space from the projections.]

4.2.4.6. Diffuse versus Direct Radiation

The quantity and size distribution of aerosols in the atmosphere alters both the amount of solar radiation reaching the Earth's surface and its distribution between direct radiation and diffuse radiation (ref). There are observed trends in both quantities in many parts of the world, usually in the direction of overall 'dimming' of around 30 W m^{-2}, with an accompanying increase in diffuse radiation of up to 20 W m^{-2} (Kvalevåg & Myhre, 2007). For a constant total radiation, an increased fraction received as diffuse radiation theoretically increases net photosynthesis, since more leaves are illuminated at levels below which saturation sets in leaves exposed to direct solar radiation (Mercado et al., 2009). This is a potentially important consequence of solar radiation management schemes that involve the injection of aerosols into the stratosphere [refer to treatment of SRM in WG3].

4.2.4.7. Invasive Species

Alien species are regarded in this respect as species, whose presence and dispersal is human mediated, i.e. due to unintentional or intentional human activity. Altitudinal or latitudinal range expansions (of native species) are not considered here **[see e.g. chapter on pollination]**. However, this discrimination is under discussion and not always possible, since although a species is defined as native for a specific region, its natural altitudinal range expansion could be considered as invasion into a new environment (in this case e.g. the mountain top).

Changing air or water temperatures and precipitation regimes can facilitate the spread and establishment of alien species including host species or vectors of pathogens and other (animal-, plant- or human-) disease causing microorganisms (Dukes et al., 2009; Walther et al., 2009) but also hinder species invasions (Bradley, Oppenheimer, & Wilcove, 2009). It is almost impossible to disentangle the various drivers (e.g. climate, land use, human mediated transport, propagule pressure) and their net effects on the spread and establishment of alien species.

Since the IPCC AR4 the number of indications for the spread or presence of alien species due to climate change increased for taxa and regions globally, including the pole areas (different taxa: Walther, et al., 2009; Masters & Norgrove, 2010; plants: Bradley, Blumenthal, Wilcove, & Ziska, 2010; insects: Musolin, 2007; Robinet & Roques, 2010; mountain floras: McDougall et al., 2011; aquatic taxa: Rahel & Olden, 2008

Climate change and alien species in combination lead and will lead to novel communities, which affects existing ecological networks. Alien species combined with the effects of climate change can cause disruptions and also the formation of new ecological networks (e.g. plant-pollinator: Schweiger et al., 2010; aquatic predator-prey : Rahel & Olden, 2008).

Studies of future climate projections suggest range expansions of many alien species (e.g. forest insects and pathogens in North America: Dukes, et al., 2009, plants in Germany and Austria: Kleinbauer et al., 2010) but also show range contractions of alien plants (Bradley, et al., 2009). Interactions of affected climatic variables such as CO2 level could be highly complex and hence effects on alien species difficult to predict (e.g. experimental warming negated positive impacts of increased CO2 levels on alien plants; A. L. Williams et al., 2007).

4.2.5. Uncertainty of Future Land Use Pathways

Growth of the global human population's demand for food, feed, fiber, and fuel has accelerated in recent years, placing new pressures on terrestrial and freshwater ecosystems that can influence the response of these systems to climate change. Evidence of these interactions is reviewed in Section 4.3.4. The principal driver of this acceleration in demand is the rate at which per capita consumption is growing in emerging economies, led by China but including India, Brazil, Indonesia, and South Africa. Policy shifts favoring the expansion of biofuel production, sometimes at the expense of food crop production, have contributed to this acceleration (Lapola et al., 2010 , Searchinger et al., 2008). The rise in commodity prices results, as well, from restrictions on the rate of growth of supply that are associated with climate-related crop failure (Lobell, Schlenker, & Costa-Roberts, 2011), declines in the growth of agricultural productivity (from 3% to 1% per year 1960-1990 to 1990-2010), and possibly a shortage of arable land that is not already under cultivation, especially in the temperate zone (E. F. Lambin & P. Meyfroidt, 2011). One symptom of this imbalance is the rising price of food commodity prices since 2006 (International Monetary Fund, 2011), interrupted briefly by the global economic crisis (D. C. Nepstad, Stickler, Soares, & Merry, 2008). *In sum, the accelerating growth in global demand for food, fuel, fiber, and feed is outpacing the growth in supply*.

The trajectory of future growth in demand for land- and freshwater-based production is uncertain, and will vary depending upon economic trends and policies, which are themselves dependent upon political stability and complex political and social processes. Projections of future supply and demand for agricultural commodities indicate that there is a high likelihood that the global imbalance, in which the growth in demand for food, fuel, fiber, and feed outpaces growth in supply is likely to continue, maintaining food commodity prices 20 to 40% higher through 2020 relative to pre-2006 prices (OECD/FAO, 2010). Emerging economies have the greatest scope for increasing per capita consumption, and the growth of these economies will therefore play an important role in future land use trends. Deforestation in developing countries is now correlated with the export of agricultural commodities (DeFries, Rudel, Uriarte, & Hansen, 2010), providing an early symptom of the growing role of agricultural trade with emerging economies as the driver of land-use change.

Future expansion of the supply of land- and freshwater-based products can be achieved through increases in yield and through increases in the area of cultivation/production. The former is often associated with increases in water use, the application of fertilizers and other agro-chemicals, and in nitrogen loading associated with livestock confinement. The latter often implies conversion of natural ecosystems to cropland, grazing land, and tree plantations, or intensified management of natural ecosystems. Suitable land for agricultural expansion is concentrated today in South America, Africa, and Eastern Europe (E. F. Lambin & P. Meyfroidt, 2011), and much of this land currently supports natural ecosystems. Most of the expansion of agricultural, livestock, and tree-based production by 2030 is likely to take place in South America (led by Brazil) and Africa (Eric F. Lambin & Patrick Meyfroidt, 2011), and could drive the conversion of forests and savannas to agriculture and forestry, and changes in the fire regime.

One of the uncertainties about future land use trends is climate policy. The most advanced component of the post-2012 UN climate treaty (UN Framework Convention on Climate Change) is a mechanism that would compensate developing nations that reduce their emissions of greenhouse gases from deforestion and forest degradation. It is in the context of REDD that deforestation rates of the Brazilian Amazon [as of 2010] had declined 67% below their average rates for 1996 to 2005 (?INPE, 2010), and part of this decline is likely to be a result of government policies (B. Soares-Filho et al., 2010). This reduction is part of a broader global trend towards declining tropical deforestation rates (Friedlingstein et al., 2010), although the causes of this global trend are unknown.

Recent increases in the demand for food, fiber, fuel, and feed are outpacing increases in supply, and this imbalance is likely to continue, creating elevated pressure on natural terrestrial and aquatic ecosystems that occur on or near land that is suitable for agricultural expansion.

4.3. Vulnerability to Climate Change and the Positive and Negative Impacts

4.3.1. The Importance of Changes in Disturbance Regime

The species composition at a given location is determined by three factors: the physiological tolerance of the species in relation to the range of conditions experienced at the site; the interactions with other species, including competition, predation, pests and mutualists; and whether the species have been able to reach the location in evolutionary or recent times (ref). The average environmental conditions are often less of a determinant of species ranges than the extremes, such as the occurrence of exceptionally cold or hot days, droughts exceeding a certain duration (ref). The changes in probability of such extremes is typically disproportionately larger than the relative change in the mean (ref, but see Diffenbaugh, Pal, Trapp, & Giorgi, 2005). Competitive exclusion would tend to lead to a small set of dominant species if it were not for occasional disturbances that relieve the competitive pressure and create opportunities for marginalised species. Fire, floods and strong winds are all examples of biodiversity-sustaining events, provided that their frequency and intensity does not deviate greatly from the regime that prevailed at the location in evolutionary time. Although non-endemic species are more easily transported to new locations for which their physiology is adapted in the contemporary, interconnected world than in the past, their establishment usually requires a disturbance that weakens competition from pre-established species (ref).

It is thought that widespread compositional shifts resulting from the combined effects of global change forcings will be relatively abrupt and associated with changes in the disturbance regime, rather than reflecting a gradual and continuous expansion of ranges and changes in abundance. A ‘disturbance regime’ refers to the totality of different types of disturbance events in a system, each characterised by their probability-intensity function and other relevant attributes, such as their seasonal distribution (ref).

4.3.2. Evidence of Change in Ecosystems

Hierarchy from physiological through demographic to functional

Many properties of ecosystems are studied, providing a rich information base from which evidence of whether change is occurring may be obtained. Site-specific phenology studies appear to provide a major portion of the directly-observed evidence base for changes in terrestrial ecosystems over several decades - generally speaking it is this aspect of ecosystems that appears to have been systematically monitored for longest. Other ecosystem characteristics such as biomass and productivity only began to be monitored when concern about climate change became prominent, whereas phenology was studied for its own sake before that. In addition to direct observations, information on past changes can also be obtained by studying aspect of life forms that retain information on their growth and functioning in the past, such as tree rings and stable carbon isotope composition. More recently, satellite observations allow for a wider and more complete geographical coverage although data are only available for the last 20-30 years.

All these information sources have their own challenges affecting the level of confidence in the observed change. Coverage of site-specific studies is not uniform across the globe – in many cases the records are mainly in Europe and North America, although there are some in high latitudes and the tropics too. The various types of site-specific record share the common challenge of trying to establish a large-scale signal.

A difficulty with using satellite imagery for long-term monitoring is changes in instruments. Records for some individual instrument are not very long. Advanced Very High-Resolution Radiometer (AVHRR) data are available from 1982 onwards, and studies based on this were cited in AR4, and in more recent studies (e.g.: Potter, Kumar, Klooster, & Nemani, 2007) MODIS became operational in 2002/3 **[check exact date]**and is widely used, but comparison of data from one instrument against another relies on certain assumptions. Clearly it is vital to avoid spurious trends or shifts in observed quantities arising from instrumental changes.

A key issue is whether change is significant or not in the context of past variability. The question is attribution of changes to their causes is also of paramount importance if the processes of change are to be understood and future changes are to be predicted. As well as the need to distinguish climatic and non-climatic drivers of ecosystem change, the issue of joint attribution is important – distinguishing the impacts of anthropogenic climate change from those of natural variability. For terrestrial systems, some drivers of change may be considered "non-climatic" in that they are not meteorological, yet are closely related to anthropogenic climate change (e.g.: physiological effects of changes in atmospheric composition, and impacts of anthropogenic land cover change).

[[Figure suggestion: global map(s) of coverage of on-the-ground studies of ecosystem change:
[Show map of sites in ITRDB – from Gedalof and Berg 2010 fig1 (is this the complete set from ITRDB?)
[also map of phenological record sites – Menzel?]
[also map of biomass sites – RAINFOR – Phillips?]
[also map of flux tower sites]
[also map of sites where species distributions have been studied – if such a map exists
[could either have these on separate panels or overlaid on a single map]]

[Each of the following sections needs something on the extent to which the changes discussed have been formally attributed to anthropogenic climate change, climate change/variability in general, or other drivers].

4.3.2.1. Phenology

A large number of site-specific studies, and also more recently satellite imagery, allow monitoring of phenology. This especially applies to plant species (budburst, flowering dates etc.) but a number of studies of animal, bird and insect species are also available. There are many sites across some regions (e.g.: Europe) but fewer across other regions (e.g.: Africa) so evidence base varies geographically. Some sites have records extending back several decades, or in exceptional cases centuries. Results vary widely, although the predominant picture appears to be one of spring season events such as budburst and first observation of species showing a general trend towards earlier in the year. However not all species in all sites show such trends – some show no significant trend, others show a trend towards later dates. **[Need to discuss establishment of "significance" here – may be different in different studies. It is important to distinguish real trends from "random walks".]**

[the following still too much bullet point style?]
For example, Phenological records in Spain from 1943-2003 show changes occurring since 1970s – lead unfolding, flowering & fruiting dates advancing by -0.48, -0.59 and -0.32 days yr-1 (Gordo & Sanz, 2009). Less consistent change in leaf falling dates – some advancing, some delaying. Growing season lengthened overall by 18 days (Gordo & Sanz, 2009). In Switzerland: 38 years of pollen data (1969-2006) indicate start of flowering in birch became 15 days earlier (Frei & Gassner, 2008).

Satellite imagery also suggests general shifts in high-latitude vegetation phenology at large scales. Phenological changes are not limited just to plant species. Animal, bird and insect species are also studied, particular egg-laying dates and the timing of spring emergence. Changes in abundance, distribution and phenology of woodland bird species in temperate regions – Leech and Crick, 2007, Ibis . **[Review paper - this mostly cites material that would have been available for AR4 so need to look for more recent work, but the reference list in this paper provides a good starting point)** The earliest appearances of butterfly species have been documented in several UK records since 1970s, generally showing the earliest appearance to be trending towards earlier in the year (?Sparks & Yates, 1997)

Phenological studies of multiple species and trophic levels at the same site are particularly valuable. An 80+ year record of phenology of a number of plant and animal species in New York state, USA indicates temporal trends in the flowering and first sighting of a number of plant species, although the trends differed in magnitude and even direction. Some species showed no trends. Some animal species also showed phenological trends. (Cook et al., 2008– **[include figures from this paper?]**).

A number of studies have linked observed phenological trends to trends in meteorological variables, especially growing degree days, providing evidence of a link to climate [give examples]. However, the second stage in the joint attribution problem (establishing the fraction of change attributable to anthropogenic climate change as opposed to natural variability) is still rarely carried out.

4.3.2.2. Vegetation Productivity

Earth observation can in principle be used to monitor aspects of vegetation cover. A commonly used metric is Normalised Difference Vegetation Index (NDVI). Literature on this for boreal forest regions in particular. AR4 reported previous evidence for widespread "greening" trends at high latitudes **[check what was specifically said]**, but more recent evidence suggests that such trends have not continued at the same rates or been geographically uniform up (Goetz, Mack, Gurney, Randerson, & Houghton, 2007). More than 25% of North American forest areas (excluding areas recently disturbed by fire) showed a decline in productivity and no systematic change in growing season length, particularly after 2000 (for records extending to 2005 as measured by AVHRR).

Tree ring records can be indicator of ecosystem change / variability, sometimes extending well back into the past (before human record-keeping). Ring width and wood density can indicate annual tree growth, and stable carbon isotopes within the rings can also indicate changes in physiological functioning. Variations in tree rings can arise from a variety of factors, including temperature, moisture stress, CO2 fertilization and ozone damage. Correlations with temperature in temperature-limited locations, particularly high latitudes and altitudes, lead to their widespread use as a climate proxy. **[However here the aim of the analysis is on tree rings as indicators of vegetation growth and functioning]**.

Tree ring records indicate variability in growth from year to year and decade to decade, often extending back several decades or even many centuries. Techniques such as principle components analysis (PCA) are used to discern the different patterns of variability in time. Different sites, or different individual trees at the same site, can exhibit different patterns of variability. [more detail on combining multiple records?].

For much of the 20th century, a number of records have shown a general tendency of increased tree growth [Briffa, Idso, Wilsonwhich often correlates with temperature. Direct CO2 effects, in terms of increased growth relative to drought **[is this sufficient? does it allow for identification of CO2 effects in non-drought affected systems?]**, have been identified in approximately 20% of the sites in the International Tree Ring DataBase (ITRDB) – ?Gedalof & Berg, 2010– and studied in detail at some sites (e.g.: Koutavas, 2008) [discuss CO2 effect here as well – how is temperature signal distinguished from CO2 signal]. However since the 1980s a number of records show a decline in tree growth [Wilson? Others?]. A number of possible causes have been suggested for this, including increasing water stress and ozone damage [references]. However, most tree ring chronologies only extend to the 1980s (Gedalof & Berg, 2010) so conclusions for more recent dates are based on less evidence.

It should be noted that tree ring studies may not be representative of forests in general, as most studies have been specifically designed to examine growth in response to environmental changes (Gedalof & Berg, 2010). Sites which are not sensitive to environmental changes may therefore be under-represented.

4.3.2.3. Vegetation Biomass

Several dozen sites across the moist tropics have been monitored intermittently [is this a fair term?] to estimate changes in forest biomass. The RAINFOR project [Phillips, Baker, Malhi] involved across tropical measuring breast-height girth of trees to estimate biomass, on occasions several years apart. A general trend of increasing forest biomass across tropics is seen, although a fall in biomass in Amazon was measured after the 2005 drought **[get info on response to 2010 drought]**

[have these observations been assimilated into models as a re-analysis...?]

4.3.2.4. Species Distributions and Extinctions

4.3.2.4.1. Plant species

Most large-scale changes in vegetation appear to be due to land use / land abandonment. The main evidence of changes where climate may play an important role is generally in colder regions: boreal forests, tundra, mountains, and the polar regions (including Antarctica)

In the boreal forests there is evidence of migration of "keystone ecosystems" in upland and lowland treeline of mountainous regions across Southern Siberia (Soja et al., 2007) **[cite other papers here]**. In mountainous regions, more species appear to be surviving at high altitudes: for example, an increase in species richness was seen in measurement plots in Austrian Tyrol, between 1994 and 2004 (approx 11.4 species per plot in 1994 increased to approx 12.7 species per plot in 2004; Pauli, Gottfried, Reiter, Klettner, & Grabherr, 2007) **[cite other papers here]**

In the maritime Antarctic, 2 native vascular plants, Antarctic pearlwort (*Colobanthus quitensis*) and Antarctic hair grass (*Deschampsia antarctica*) hae become more prolific over recent decades – vascular plants in Antarctica may benefit from warming more than mosses due to efficient acquisisition of N released in faster decomposition of soil organic matter with a warming climate (Hill et al., 2011)

However, some large-scale changes are also being seen outside of cold regions. For example, woody vegetation is encroaching into shortgrass steppe / savanna / cerrado worldwide. **[several papers – eg: Ed Mitchard forest / savanna boundary]**

4.3.2.4.2. Animal species

[Discuss literature on changes in species ranges – eg: northern limit of ranges of a number of UK species documented as shifting northwards…]

Species extinctions are ongoing, and increasing numbers of species are becoming increasingly endangered (Butchart et al., 2010) but predominantly these appear to be directly due to direct human intervention through habitat loss or hunting. Attribution of individual extinctions specifically to climate change currently is not possible, or at least not clear. The extinction of the Golden Toad, which became iconic as a reputed climate change-driven extinction, appears to be linked to climate variability not change (Anchukaitis & Evans, 2010).

4.3.2.4.3. Disturbance regimes

["extreme" fire years now occurring quite often in Siberian boreal forest (Soja, et al., 2007)]

Global scale Earth observation data on burnt area / fire intensity becoming available. Can sometimes be difficult to reconcile different datasets, especially from different instruments as they measure different things (e.g.: NDVI, brightness temperature) which pick up different aspects of fire behaviour with different levels of confidence. Satellite data extend back to the mid-1990s. Before this, other data sources such as fire service records (Australia?) and records of visibility reported at airports (Indonesia; R. D. Field, Werf, & Shen, 2009) are sometimes used. Interactions between land use and climatic conditions form a key component of landscape fire activity. In Indonesia, fires associated with comparable drought conditions is reported to be larger as a result of human land use activity (R. D. Field, et al., 2009; also Marengo et al?)

4.3.2.4.4. Transpiration and its role in the terrestrial water cycle

Evidence from a data-driven empirical model and process-based land models suggests that global evapotranspiration rose from the 1980s to the late 1990s but this trend then ceased, with increasing soil moisture limitations being cited as the cause (Jung et al, 2010). Impacts of rising CO2 on plant physiology, with reduced opening of stomata causing decreased transpiration, may make a small contribution – stable carbon isotopes show that intrinsic water use efficiency increased in a temperate semi-natural grassland since 1857 (Köhler et al, 2010) and global coupled vegetation-hydrology models show a small impact of CO2 physiological forcing on evapotranspiration and river flows (?Gerten, et al., 2008). Detection of ecosystem influences on land hydrology depend critically on the hydrological observations - AR4 reported work by Gedney et al (2006) claiming to have detected the effects of CO_2 physiological forcing of vegetation (decreased transpiration) in contributing to increased large-scale runoff in the reconstructions of Labat et al, but more recent datasets showing different trends in some areas (eg: Dai et al, 2008). Trends in the recent datasets still appear to show a small direct CO2 contribution although these are smaller than the precipitation contribution (?Gerten, et al., 2008). However the anthropogenic component of the precipitation contribution has not yet been established, and other direct anthropogenic contributions to runoff also need to be considered (Dai et al, 2008) so a full-system attribution of anthropogenic CO_2 emissions (and other greenhouse gases and other anthropogenic effects) has yet to be provided.

[INSERT TABLE 4-2 HERE
Table 4-2: sources of information on observed ecosystem change.]

[See <WGIIAR5-Chap4_ZODfigs.pdf> for Section 4.3.2 figures, labeled Figures 4-4 to 4-8 to facilitate comments.]

Make figure(s) synthesising time series data of vegetation change / variability of different kinds, over various timescales. AR4 "Observed change" chapter only included 1 example of such a time series figure (for a few phonological changes in Germany), but I think many more can and should be shown now, covering different places worldwide and different aspects of change, eg:

- **Phenological records (decades – couple of centuries)**
- **Tree rings (decades to centuries)**
- **Biomass (years)**
- **Species distributions (how to quantify?)**
- **NDVI + other EO date – years / couple of decades**
- **Position of northern treeline???**
- **Position(s) of altitudinal treelines???**

As well as showing what changes are being seen (or not), this will also show which types of records are available and for how long – and also whether any consistent signals are emerging. A few examples of the kind of data available are shown below.]]

[possibly show time series of drivers of change for context – CO2, temperature, precip, O3, area of land under agriculture….. May be difficult to be comprehensive with specific relevant quantities as some will be geographically quite heterogeneous – eg: precip – but may be important to provide context for attribution.]

4.3.3. Species Changes in Abundance at Local to Global Scale [Migratory Species]

[This section focuses on three types of species level responses: shifts in species range, changes in abundance (including local extinctions), global extinctions and changes in species diversity: will be changed into fluent text]

Observations (since AR4 - Thomas, Franco, & Hill, 2006, Hickling, Roy, Hill, Fox, & Thomas, 2006; Lenoir, Gegout, Marquet, de Ruffray, & Brisse, 2008, Beever et al. 2011, Feeley, Davies, Perez, Hubbell, & Foster, 2011, Crimmins, Dobrowski, Greenberg, Abatzoglou, & Mynsberge, 2011, but see Rowe, Finarelli, & Rickart, 2010):

- Increasingly overwhelming evidence for recent, climate-related range shifts in nearly all groups of terrestrial organisms.

- Large differences in the speed of range shifts: e.g., butterflies = fast, herbaceous plants = moderate, trees = slow, but clear trend
- Clear differences in ability of species to adapt to range shifts: migratory birds vs. non-migratory birds, butterflies and capacity to change host plants or not, etc.
- Uphill, poleward movement an oversimplification of response which may be at least equally sensitive to regional precipitation (Crimmins, et al., 2011, Lenoir, Gégout, Dupouey, Bert, & Svenning, 2010)

Model projections:

- Large range shifts projected due to CC based on a very broad range of models. However, explosion in niche modeling since AR4 report (Dawson et al. 2011). Some evidence that niche models produce higher rates of range shifts than other kinds of models and considerable discussion of limitations of this approach (Morin & Thuiller, 2009, Kearney, Wintle, & Porter, 2010, Cheaib et al, submitted).
- - Migration rates remain a very large source of uncertainty (Thuiller et al., 2008). Speed required to maintain thermal envelope is high and differs greatly across biomes (S. R. Loarie et al., 2009)
- - Model validation has progressed, but still is a weak point of scenarios work (Araujo, Pearson, Thuiller, & Erhard, 2005, Dawson et al. 2010)
- Range shifts will cause problems in terms of protecting species & ecosystems (see below)
-

Species abundance - Main points

- Projected local extinction rates are extremely variable, ranging from near zero to more than 80%. Highest rates in equatorial regions with equatorial migration barriers (e.g., Iberian peninsula). Projected local colonization rates are extremely variable, but can be very high (Bellard et al., submitted)
- Impacts on abundance highly variable depending on area in range studied. CC could increase pop sizes some currently threatened species.
- Local changes in species abundance could have large impacts on conservation strategies, ecosystem services, natural resource management, etc. This may be the most visible and economically import impact of CC on "natural" systems.
-

Global species extinctions

Climate change impacts on species extinctions have received considerable attention since the AR4 report indicated that "*approximately 20-30% of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5-2.5°C.*" Studies using wide range of methods to estimate extinction risk indicate, on average, project large increases in extinction rates compared to current rates of extinction and very large increases compared to the paleontological record (Pereira et al., 2010, Bellard et al. submitted). However, the uncertainty in projected future extinction risk due to climate change ranges from below 1% to above 50% of species by the end of the century in the species groups that have been studied (Pereira et al. 2010). In addition, methodological challenges, large variation in the climate sensitivity of species groups and unknowns in how extinction risk will be translated into realized extinctions over the next century mean that there is very high uncertainty concerning the fraction of species that are likely to go extinct over the next century (?Willis & Bhagwat, 2009, Kuussaari et al., 2009, ?Dawson, et al., 2011, ?McMahon et al., 2011, Tedesco et al. submitted). There is, however, a clear concensus that climate change will result in shifts in species ranges, and that range contractions and constraints on migration for many species, especially in the context of highly fragmented habitats and other global change pressures, will greatly increase extinction risk over the coming century (refs).

Takehome message:

Most species ranges are virtually certain to move 10s to 100s of km over the next several decades in response to projected climate change. The paleontological record, recent trends and a very broad range of models all converge on this message. This is virtually certain to lead to high rates of local species turnover that will pose serious challenges for species conservation, as well as for societies, policy makers and natural resource managers. The primary uncertainties in species range shifts are related to climate scenarios and the speed with which species will move. Projected 21st century climate change impacts on global species extinctions are characterized by high uncertainty, but very large increases in species extinction risk due to climate change in several studies argues in favor of strong climate mitigation. – **[too policy prescriptive ?]**

4.3.4. Impacts on Major Systems [Thresholds, Vulnerability, Extremes, Feedbacks]

4.3.4.1. Forests and Woodlands

4.3.4.1.1. Impacts of climate change on boreal forests

A complex message is emerging from literature, with projected changes being somewhat model-dependent (especially according to which processes of change are considered – a big issue is whether fire is included or not). Most projections suggest general poleward expansion of forests into tundra regions, and/or general shift in balance towards more temperate plant functional types (eg: evergreen needleleaf being replaced by deciduous broadleaf, or in colder regions, deciduous needleleaf being replaced by evergreen needleleaf; A. H. Lloyd, Bunn, & Berner, 2011). However, if fire is considered, some models suggest something of a "boreal forest die-back" due to increased fire activity with climate change. **[Eg: DGVM Intercomparison paper, Sitch et al., 2008].**

A number of the Earth System Models being run for AR5 now included dynamic vegetation, so projections of these directly from these models will be available for this assessment). These include feedbacks from vegetation change to local climate (eg: via surface albedo) so are arguably more consistent than "offline" models – however they are also vulnerable to the inherent biases in climate models. Several studies on "offline" model projections.

TABLE Summarising key results from studies relating to climate change and boreal forests
[To be done]

[INSERT FIGURE 4-9 HERE
Possible Figure 4-9: Changes in zonal mean tree cover. **[This figure shows all latitudes but it may be appropriate to just show boreal forests]**. Zonal mean coverage of broadleaf (left) and needleleaf (right) trees, showing absolute values simulated for 2000 and 2100 (top) and the difference between 2100 and 2000 (bottom) for 4 RCP scenarios with the HadGEM2-ES ESM. **[Key point to make here is that the poleward expansion of boreal forests in general and both PFTs in particular can be seen on the left hand side of the plots, with NL trees expanding at northern latitudes but being replaced by BL trees at the southern side of the boreal zone. However NB this model does not include fire]**

4.3.4.1.2. Impacts of climate change on temperate forests

The largest areas of temperate forest are found in eastern North America, Europe and eastern Asia. The overall trend for in these regions until recently has been an increase in growth rates of trees and in total carbon stocks in forests that has been attributed to a combination of increasing growing season length due to climate warming, rising atmospheric CO2 concentrations, nitrogen deposition and forest management (Paio et al. 2011). The relative contributions of these factors has been the subject of substantial debate (Boisvenue & Running, 2006).

There are, however, several recent disquieting indications that temperate forests and trees are beginning to show signs of climate stress including: a decline in tree growth rates, increasing tree mortality (see box) and changes in fire regimes, insect outbreaks and pathogen attacks. Several studies find that tree growth rates in temperate forests have recently passed their peak and that the decline in tree growth rates can be attributed to climate, especially due to drought or heatwaves (Charru, Seynave, Morneau, & Bontemps, 2010, Silva, et al., 2010). Extreme climate events have also had a major impact on temperate forests over the last decade. For example, severe forest fires have occurred in several regions over the last decade, for example in Russia during the exceptionally hot and dry summer of 2010 (refs). The complex interactions between climate and forest management in determing susceptability to extreme events make it difficult, however, to clearly attribute these events to recent climate warming (refs).

There has been a tremendous increase in the number modeling studies of climate change impacts on temperate forests at the species and biome levels since the AR4 report. As was the case in the AR4 report, nearly all models continue to project regression of temperate tree species and forests over the next several decades at their equatorial or low altitude range limits, and increased growth and potential for colonization in new favorable climates at their poleward or high altitude limits. The most signficant advances since the AR4 report have been the increase in multi-model studies of climate change impacts, greatly improved coverage of eastern Asia, an increase in the variety of modeling approaches used and modest improvements in model validation.

At the biome level, there is considerable uncertainty in the sign and the magnitude of the response of temperate forests to climate change. A quantitive comparision of DGVM models showed that for identical climate projections for the end the century, temperate forests are variously projected to substantially increase in total carbon storage with gains in tree cover in eastern North America and Europe vs. projections of substantial reductions in total cargon storage and loss of tree cover in favor of herbaceous species (Sitch, et al., 2008). Projections based for eastern Asia are less variable and temperate forests remain carbon sinks over the coming century, with carbon storage generally peaking by mid-century and then declining (?He, Ju, Wen, Lu, & Jin, 2007, Sitch, et al., 2008, Ni, 2011; Peng et al., 2009). However, regional vegetation models for China predict that northward biome shifts of temperate forest will be substantial (?Weng & Zhou, 2006, Ni, 2011). There is little indication from models or observations that the responses of temperate forests to climate change are caracterized by tipping points, because the feedback mechanisms operating in boreal and tropical forests appear to be less important in temperate climates (Bonan 2008).

At the species level, all models predict that overstory and understory species will shift their distributions poleward and up in altitude in all regions of the world in response to climate change. Projected range shifts vary from several km per decade to hundreds of km per decade. Multi-model comparisons for temperate forests illustrate that there are, however, very large differences in species response and that models differ greatly in the severity of projected climate change impacts on species range (Kearney, et al., 2010, Morin & Thuiller, 2009, Cheaib et al. submitted). Tree growth models generally project increased tree growth at poleward and high altitudinal range limits over most of the next century (Ni, 2011). New approaches to modeling tree response based on the senstivity of key life-history stages suggest that climate change impacts on reproduction could be a major limitation on temperate tree distributions (Morin, Augspurger, & Chuine, 2007). Comparisons with paleo data have helped improve confidence in the ability of models to project future changes in species ranges (Pearman et al., 2008, J. R. M. Allen et al., 2010, Garreta et al., 2010). Model projections are qualitatively coherent with observations that temperate forest species are already moving poleward and up in altitude, most likely due to climate warming at the end of the 20th century (Lenoir, et al., 2008).

[Model projections of fires, pest outbreaks, etc. - Fire risk generally predicted to increase. Expansion of pests poleward and up in altitude - to be written]

Overall, there is overwhelming evidence from observations and models that climate change has and will result in ranges shifts of temperate forests, as overstory and understory species move based on species-specific responses to climate change. These shifts will alter biodiversity and ecosystem services from temperate forests (Dale, Tharp, Lannom, & Hodges, 2010). Major uncertainties are whether these climate change impacts will be characterized by gradual replacement of species, continued stimulation of tree growth and forest carbon storage over the coming century, or by massive dieback at range margins, greatly increased disturbance rates, reduced tree growth and conversion of temperature forests from net carbon sinks to carbon sources (Dale, et al., 2010).

4.3.4.1.3. Impacts of climate change on tropical forests

The response of closed-canopy, tropical forests to climate change depends upon their response to changes in rainfall, temperature, and atmospheric CO2 concentration. These effects are superimposed upon the direct influences of human activities, including the harvest of individual plants or animals, management interventions to favor some species or structural features over others, conversion of forests to cropland or grazing land, and changes in ignition sources and fire regimes.

Droughts are likely to be more extreme and more frequent in some tropical forest regions under higher levels of radiative forcing (**[WGI]**; Malhi et al., 2009; Betts, Sanderson, & Woodward, 2008). Rainfall is already declining in the Amazon region (Brando et al., 2010), although there is no evidence that this decline is driven by global climate change. Severe droughts in the Amazon Basin during the last decade, including the two most severe droughts on record (in 2005 and 2010, ?Marengo, Tomasella, Soares, Alves, & Nobre, 2011 and Lewis, Brando, Phillips, van der Heijden, & Nepstad, 2011), have provided opportunities to observe the response of this region's forests to climatic extremes. In 2005, a drought threshold was surpassed; tree mortality increased in forest plots across a large portion of the Basin (Phillips, et al., 2009). This finding is consistent with two large-scale forest manipulations, in which rainfall was partially excluded from forest plots. After three years of severe drought simulation, tree mortality rose abruptly and was highest for large canopy trees (D. C. Nepstad, Tohver, Ray, Moutinho, & Cardinot, 2007, Fischer et al. 2008). Severe, episodic droughts, which are expected to increase in frequency in some tropical forest regions, exceed the drought threshold of some tree species, changing forest structure for years to come.

One of the most important effects of drought-induced tree mortality is fire susceptibility. During years of average rainfall, mature forests in the Amazon, Southeast Asia, and Central Africa have low levels of suceptibility to fire because of high levels of forest floor moisture throughout the year (Cochrane, 2003). This susceptibility increases through elevated tree mortality, which allows more radiant energy into the forest understory, lowering the moisture content of the fine fuel layer (Ray, Nepstad, & Moutinho, 2005). Selective logging (Uhl & Kauffman, 1990), severe drought, and forest fire itself all increase forest susceptibility to fire by killing (or removing) trees. Land use activities, which often depend upon fire to help convert forests to croplands and pasture, and to manage lands that are already cleared, provide an expanding source of ignition points for fire-susceptible tropical forests (Malhi, et al., 2009). In 1998, during a severe drought associated with an El Nino Southern Oscillation episode, fire burned large areas of forest in the Amazon, Borneo, and Mexico (Alencar, Nepstad, & Vera Diaz, 2006, ?Curran et al., 1999). Severe droughts increase moist tropical forest susceptibility to fire, exposing these ecosystems to fire incursions which kill trees, further increasing susceptibility.

The effects of rising atmospheric CO2 levels may be influencing the growth rates and composition of tropical forests. Permanent forest plots in the Amazon Basin and Central Africa are undergoing significant changes in tree composition, with slow-growing, high wood-density species declining and fast-growing, light-wooded species increasing; this compositional change is consistent with predictions of the shifts that would be expected through atmospheric CO2 fertilization (Lewis, 2006). In both regions, a net increase in forest biomass is also observed that may be a response to CO2 fertilization (Phillips, et al., 2009; Lewis et al. 2010). CO2 elevation increase water use efficiency of plants, and therefore diminishes the effects of temperature increase (and higher evapotranspiration) on tropical forests. Preliminary analyses suggest, however, that the effect of temperature increase on forest water balance is three times greater than the effect of lower stomatal conductance (Malhi, et al., 2009).

Tropical forests are probably close to their temperature optima. Rising maximum daily temperatures such as those predicted for the region could close to some of the biochemical limits of metabolic and photosynthetic functions (?J. Lloyd & Farquhar, 2008).

The integrated effects of climate change and land use change on tropical forests are best understood for the Amazon Basin. Reductions in rainfall simulated using AR4 climate model runs are anticipated primarily in the eastern Amazon region, and would be sufficient to reduce rainfall to that typical of seasonal tropical forests, but not low enough to force a shift to savanna (Malhi, et al., 2009). This drying trend could be exacerbated by changes in rainfall driven by deforestation itself (Dias et al. 2007). When the increased intensity of drought events, projections of future land use (B. S. Soares-Filho et al., 2006) and fire are included in the analysis (Malhi, et al., 2009, D. C. Nepstad, et al., 2008), however, it is likely that more than half of the forests of the eastern Amazon will be cleared, logged, burned, or damaged by drought by mid-Century.

4.3.4.2. Rangelands and Drylands

4.3.4.2.1. Savannas

Savannas are, by definition, coexistences of trees and grasses. Therefore all the global change considerations that apply separately to trees and grasses also apply in savannas, but with the additional consideration of how their differential effects on the tree and grass functional types will alter the structure (ie fractional tree cover) of the savanna. Structure in turn strongly influences the herbaceous species composition, number and abundance of herbivores and carnivores, frequency, type and intensity of fires, carbon storage and supply of ecosystem services such as grazing or fuelwood (Refs). Savannas are characterised by annual to decadal relatively low-intensity fires, which are not only a key factor in maintaining the tree-grass proportions, but constitute a major global source of pyrogenic emissions from land to atmosphere (refs). Since savannas in the limited sense of neo-tropical vegetation with grasses and more than 10% but less than 60% tree cover occupy about 12% of the global land surface (refs), small changes in tree cover can have globally-significant effects on carbon storage and the emissions of radiatively-active gases and particles. In a looser sense, mixed tree-grass systems throughout the world, and of natural or human-created origin, may occupy over a third of the land surface (ref).

There is evidence from many parts of the world that the tree cover and biomass in savannas has increased over the past century (Scholes & Archer, 1997, and other references). In the process the mean carbon density (carbon stored per unit land area, in the soil and tree biomass) increases (refs), but the grazing potential decreases (refs). The increasing tree cover in savannas has largely been attributed to changes in land management, such as continuous high grazing livestock pressure and reductions in the frequency and intensity of fires (refs). It has been suggested that rising CO2, stimulating the growth of trees (with a C3 photosynthetic system) more than that of grasses (predominantly C4 in the tropics), may be implicated as a cause or predisposing factor (Archer ref), possibly acting to relieve a demographic bottleneck that keeps trees trapped within the flame zone of the grasses (Bond). The rising global mean air temperature, changes in precipitation and other changes that parallel rising CO2 must be considered as potential causes as well.

Elevated CO2 experiments in savannas (Ash et al) or with savanna saplings (?Kgope, Bond, & Midgley, 2010) support the hypothesis that the competition between trees ad grasses may be altered in the favour of trees under doubling of the atmospheric CO2 concentration above the preindustrial level. The spatial distribution of grasslands above savannas on elevational gradients suggests that a warming also favours trees (refs). The ubiquitous observation of strong contrasts in the degree of savanna thickening between land parcels with the same climate but different land use histories further implies that land management plays a significant role. As yet there are no definitive experiments that can attribute the causes of savanna tree cover changes to climate change or management, or between rising CO2 and temperature.

4.3.4.2.2. Grasslands and shrublands

Changes in rainfall patterns may have large effects on a wide range of biological processes of grasslands and shrublands, such as seed germination, seedling establishment, plant growth, community composition, and population and community dynamics. In a simulation experiment, (2009) found that delayed watering led to decreases in plant community productivity and to delays in flowering time, in terms of both date and number of days of water supply in a Mediterranean semiarid community. Species diversity was not affected by watering delays; however, it was reduced by changes in frequency, amount and seasonality.

Drawing on relevant published studies, Ravi, Breshears, Huxman, & D'Odorico, (2010) found that changing climate and land use have resulted in increased in aridity and higher frequency of droughts in drylands around the world. An increasing dominance of abiotic controls of land degradation, in particular hydrologic and aeolian soil erosion processes is predicted. These changes in climate may alter the relative importance of wind versus water erosion in dryland ecosystems. In the Mongolian steppe, the drought drastically reduced above ground phytomass and soil water, but did not substantially affect belowground phytomass that was not severely damaged by the drought. However, the poorly resilient species did not recover to pre-drought levels, suggesting that the response time scales differed among species (Shinoda, Nachinshonhor, & Nemoto, 2010).

(2009) reviewed the effectiveness of in situ rainwater harvesting (RWH) to face climate change impacts like droughts in sub-Saharan Africa. Farmers applying in situ RWH practices profit from higher food security and higher income, but RWH practices may strengthens conflicts between a nomadic and a sedentary population.

Somner et al. (2010) found that relative changes in plant species richness (CSR) increase with increased projected temperature rise across all analysed IPCC emission scenarios. The magnitude and direction of CSR change are geographically highly non-uniform across all modeled scenarios. In most temperate and arctic regions, a CSR increase is expected, while the projections indicate a strong decline in most tropical and subtropical regions. It means that countries least responsible for past and present greenhouse gas emissions are likely to incur disproportionately large future losses in CSR, whereas industrialized countries have projected moderate increases.

Nighttime warming and N fertilization were found to cause rapid soil and plant community responses during one monsoon season in a Chihuahuan semi-arid desert (Collins, Sitch, & Boucher, 2010). The sensitivity of this desert system to key drivers of global environmental change suggests that further increases in temperature and atmospheric deposition will likely alter community structure and ecosystem functioning in this and other aridland ecosystems.

ENSO was invoked as having a strong influence in vegetation burning in Colombian grasslands, which represented the vegetation most affected by fires every year in terms of burned area (standardized by their total area), followed by secondary vegetation, pasture and forests (Armenteras-Pascual et al., 2011).

4.3.4.2.3. Deserts

The deserts of the world, defined as areas with an arid or hyperarid climate regime, occupy xx% of the global land surface (ref). Their present extent may increase in the coming decades, despite the overall projected increase in global rainfall, due to the strengthening of the Hadley circulation (ref) which determines the distribution of most desert lands in areas affected by the descending limbs of the Hadley cells, corresponding 15-30° N and S. While sparsely populated, the people in deserts and desert fringes are amongst the poorest in the world (ref). Two special circumstances of desert ecology are important with respect to climate change. Most deserts are already extremely hot, and therefore further warming is likely to be physiologically injurious rather than beneficial. Secondly, the ecological dynamics are rainfall event-driven (Holmgren et al., 2006), often involving the concatenation of a number of quasi-independent events.

4.3.4.3. Wetlands and Rivers

Freshwater systems are already considered to be the most threatened ecosystems on the planet from human activities (Dudgeon et al., 2006; Vörösmarty et al., 2010). Most of the world's larger river systems have been moderately or heavily fragmented by dams and flow regulation (Nilsson, Reidy, Dynesius, & Revenga, 2005), with major impacts on aquatic biota, especially migratory species (Pringle, 2001). Floodplains have been transformed for intensive urban and agricultural land use to the extent that many are functionally extinct from their rivers (Tockner et al., 2008). Increases in nutrient loading and other pollutants from cities and agriculture have resulted in declines in water quality and loss of ecosystem services (see J. D. Allan, 2004). As a direct consequence of these and other impacts, freshwater systems have the highest rates of extinction of any ecosystem, with estimates of at least 10,000-20,000 freshwater species extinct or at risk. This is particularly significant considering that, although they cover less than 1% of the earth's surface, freshwater habitats support 6% of all described species, including approximately 40% of fish diversity and a third of the vertebrate diversity (Dudgeon, et al., 2006; Strayer & Dudgeon, 2010).

It is very likely that these stressors to freshwater ecosystems will continue to dominate as human demand for water resources grows, accompanied by increased urbanisation and intensification of agriculture, and river basins impacted by dams or intensive development are likely to need more management interventions to protect ecosystems (and people) than basins with free-flowing rivers (Palmer et al., 2008). Climate adaptation responses in other sectors are also very likely to exacerbate these threats, for example as societies attempt to drought-proof or flood-protect agriculture and cities with increased investments in infrastructure (see 4.4.5;Malmqvist et al., 2008; Tockner, et al., 2008). However, climate change will have significant additional impacts on freshwater ecosystems (very high confidence), particularly from altered thermal regimes, altered precipitation and flow regimes and, in the case of coastal wetlands, sea level rise. Specific aquatic habitats that are likely to be most vulnerable to these direct climate effects, especially rising temperatures, are those at high altitude and high latitude, including arctic and subarctic bog communities on permafrost, and alpine and arctic streams and lakes (see 4.3.4.4; Smith, Sheng, MacDonald, & Hinzman, 2005; Smol & Douglas, 2007). It is noteworthy that these high latitude systems currently experience a relatively low level of threat from other human activities (Vörösmarty, et al., 2010). Dryland rivers and wetlands, many already experiencing severe water stress from human consumptive use, are also very likely to be further impacted by decreased and more variable precipitation and higher temperatures. Headwater stream systems in general are also highly vulnerable to the effects of warming because their temperature regimes closely track air temperatures (Caissie, 2006).

Evidence of rising stream and river temperatures over the past few decades across several continents continues to grow (Chessman, 2009; Kaushal et al., 2010; Langan et al., 2001; Morrison, Quick, & Foreman, 2002; Ormerod, 2009; van Vliet, Ludwig, Zwolsman, Weedon, & Kabat, 2011; Webb & Nobilis, 2007), and has been linked by observational and experimental studies to shifts in invertebrate community composition, including declines in cold sternothermic species (Brown, Hannah, & Milner, 2007; Chessman, 2009; Durance & Ormerod, 2007; Ormerod, 2009). Rising water temperatures are also implicated in changes in the composition of river fish communities (Buisson, Thuiller, Lek, Lim, & Grenouillet, 2008; Daufresne & Boet, 2007), especially in headwater streams where species are likely to be sensitive to warming (e.g. Buisson & Grenouillet, 2009), and is very likely to restrict the distribution of cool-water species such as salmonids within their current range (Bartholow, 2005; Bryant, 2009; Ficke, Myrick, & Hansen, 2007; Hague et al., 2011). While these changes in river temperature regimes may also open up new habitat at higher latitudes (or altitudes) for migratory species (Reist et al., 2006), range contraction is likely to threaten the long term persistence of other fully aquatic species, including mountain-top endemics (e.g. species of spiny crayfish in eastern Australia; Ponniah & Hughes, 2004). Fragmentation of river habitat by dams and weirs restricts opportunities for cold adapted aquatic species to shift distributions to higher latitudes or altitudes, and overcoming these barrier effects represents a significant adaptation challenge (Olden, Kennard, Lawler, & Poff, 2011). Temperature impacts could be offset in small streams by reinstating or ‘over-engineering’ riparian vegetation (Davies, 2010; Wilby et al., 2010) or in larger regulated rivers by manipulating cool water releases from reservoirs (Olden & Naiman, 2010). **[How much focus should be in here about potential mitigation/adaptation responses?]**

Rising temperatures resulting in early onset and increased duration and stability of the thermocline in temperate lakes during summer (Winder & Schindler, 2004) are likely to favour a shift in dominance to smaller phytoplankton (Parker, Vinebrooke, & Schindler, 2008; Yvon-Durocher, Montoya, Trimmer, & Woodward, 2011) and cyanobacteria (Jöhnk et al., 2008; Paerl, Hall, & Calandrino, 2011; Wiedner, Rucker, Bruggemann, & Nixdorf, 2007), especially in those experiencing high anthropogenic loading of nutrients (Wagner & Adrian, 2009); with impacts to water quality, food webs and productivity (Gyllström et al., 2005; O'Reilly, Alin, Plisnier, Cohen, & McKee, 2003; Parker, et al., 2008; Shimoda et al., 2011; Verburg, Hecky, & Kling, 2003). Long-term shifts in macroinvertebrate communities have also been observed in European lakes where temperatures have increased (Burgmer, Hillebrand, & Pfenninger, 2007), noting that warming may increase species richness in smaller temperate waterbodies, especially those at high altitude (Rosset, Lehmann, & Oertli, 2010). While less studied, it is likely that tropical ectotherms will be particularly vulnerable because they will approach critical maximum temperatures proportionately faster than species in high latitude environments, despite lower rates of warming (Deutsch et al., 2008; Hamilton, 2010; Laurance et al., 2011).

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

Robust water planning arrangements that incorporate provisions for environmental flows is a key adaptation strategy (Palmer, et al., 2008; Poff et al., 2010; Aldous, et al., 2011).

Sea level rise will lead to direct losses of coastal wetlands with associated impacts on waterbirds and other wildlife species dependent on fresh water (BMT WBM, 2010; Pearlstine, Pearlstine, & Aumen, 2010; Traill, Bradshaw, Delean, & Brook, 2010) but the impact is likely to 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).

4.3.4.4. Tundra, Alpine, Permafrost Systems

The region of the High Arctic, and its tundra-dominated landscapes, has warmed more than the global average over the last century, and is changing dramatically (Kaufman et al., IPCC AR5, WG1). *This change, in turn, has already had substantial impacts on the freshwater systems, ecosystems (both plants and animals) and permafrost of the region* (Axford et al., 2009; Hinzman et al., 2005; Jia, Epstein, & Walker, 2009; Post et al., 2009; Prowse & Brown, 2010; Romanovsky, Smith, & Christiansen, 2010). The change is widespread as well, with most of the Arctic experiencing recent change in vegetation photosynthetic capacity and other aspects, particularly in areas adjacent to areas of the Arctic with rapidly retreating sea ice (Bhatt et al., 2010). *Continued climate change will cause terrestrial vegetation and lake systems of the Arctic to change dramatically in the future, in complex ways that in some cases will involve non-linear and threshold responses to warming and other climatic change* (Hinzman, et al., 2005; MacDonald, 2010; D. R. Mueller, Van Hove, Antoniades, Jeffries, & Vincent, 2009). Polar bear populations are projected to decline greatly in response to continued Arctic warming (Hunter et al., 2010), and it is likely that the populations of other Arctic animals (e.g., fox and caribou) will be affected dramatically (Post, et al., 2009; Sharma, Couturier, & Cote, 2009). Simple niche-based, or climatic envelope models are unlikely to capture the full complexity of these future changes (MacDonald, 2010).

Frozen soils and permafrost currently hold more than twice the carbon than the atmosphere and thus represent a particularly large vulnerability to climate change (i.e., warming). *Although the Arctic is currently a net carbon sink, continued warming will likely act to soon turn the Arctic to a net carbon source, that will in turn create a potentially strong positive feedback to accelerate Arctic (and global) warming with additional releases of CO2, CH4, and perhaps N2O, from the terrestrial biosphere into the atmosphere* (Elberling, Christiansen, & Hansen, 2010; Maslin et al., 2010; McGuire et al., 2010; O'Connor et al., 2010; Schaefer, Zhang, Bruhwiler, & Barrett, 2011; Schuur et al., 2008; Schuur et al., 2009). Moreover, this feedback is already accelerating due to climate-induced increases in fire (McGuire, et al., 2010; O'Donnell et al., 2011). *The rapid retreat of snowcover, and resulting spread of shrubs and trees into areas currently dominated by tundra has also already begun, and will continue to serve as a positive feedback accelerating high latitude warming* (Chapin et al., 2005).

Alpine systems are already showing a high sensitivity to on-going climate change and will be highly vulnerable to change in the future. In western North America, warming, glacier retreat, snowpack decline and drying of soils is already causing a large increase in mountain forest mortality, wildfire and other ecosystem impacts (e.g., Muhlfeld et al., 2011; Pederson, Graumlich, Fagre, Kipfer, & Muhlfeld, 2010; van Mantgem et al., 2009; Westerling, Hidalgo, Cayan, & Swetnam, 2006), and disturbance will continue to be an important agent of climate-induced change in this region (Littell et al., 2010). Alpine ecosystems already appear to already be changing in response to climate change in Africa, Tibet, the Alps, and elsewhere (C. D. Allen et al., 2010; Cannone, Diolaiuti, Guglielmin, & Smiraglia, 2008; Cui & Graf, 2009; Eggermont et al., 2010). As with the Arctic, permafrost thawing in alpine systems will likely provide a strong positive feedback in those systems (e.g., Tibet; Cui & Graf, 2009).

[INSERT FIGURE 4-10 HERE
Possible Figure 4-10: Historical observations and projections of the northern hemisphere permafrost area with a maximum thaw depth less than 3m deep. Projections are for the 4 main RCP projections from the HadGEM2-ES Earth System Model (Jones et al, submitted). Note x-axis scale change after 2100**. [NB not published yet, this is**

just preliminary results as a heads-up and to act as a placeholder. We currently think that the model overestimates the permafrost area.]

4.3.4.5. Highly Human-Modified Systems

Plantations, biofuels, urban ecosystems, cultural landscapes

[work in progress; to be elaborated]

4.3.5. Impacts on Key Services

4.3.5.1. Fibre, Timber, Forest Products

[Sketch (will be about 2.5X this long)]
Direct effects via CC impacts on tree growth - See above sections above on CC effects on different forest types. Take main messages and put in context of forest products (timber, fiber, "green" chemistry, fuel, etc.) and ecosystem services (C storage, erosion control, clean water).

Indirect effects via changes in management for climate change - Current mgmt ideas focus on i) improving resilience of forests by increasing genetic and species diversity, favoring natural regeneration and minimizing impacts of forestry activities on soils, ii) planting fast growing trees to limit the time to harvest as a means of avoiding negative effects of climate change or iii) planting species, including exogenous species, or genotypes that are likely to be resistant to higher temperatures and greater water stress. Discuss impacts on ecosystem services. – **[Coordinate with adaptation and mitigation chapters.]**

4.3.5.2. Fuel Production

Bioenergy sources include traditional forms such as wood and charcoal and more modern forms such as the industrial burning of biomass wastes, the production of ethanol and biodiesel. While traditional biofuels have been in general decline as users switch to fossil fuels or electricity, they remain dominant energy sources in many less-developed parts of the world, such as Africa, and retain a niche in developed countries. The production of modern biofuels is growing rapidly throughout the world in response to climate mitigation policies that incentivise their use (ref), or as a strategy to decrease oil dependence and thus increase energy security (Ref). The WG III chapter on energy addresses their potential as a climate mitigation strategy. Here we discuss the ecosystem impacts of large-scale land use changes related to the growing of biofuels, and the sensitivity of biofuel crops to climate change. [more text to be added] [Lou et al 2009]

4.3.5.3. Habitat for Biodiversity

[Sketch (will be about a page);
Refer to biome shifts to give an order of magnitude of problem.
Problems with protected areas losing habitat they were designed to protect - raise issues of reserve design and viability of current reserves.]

4.3.5.4. Pest and Disease Regulation, Pollination

It can be assumed, the global change results in new communities (Schweiger, et al., 2010). As these will have experienced a much shorter (or even no) period phase of coevolution, drastic changes of ecological interactions like the use of certain plants by herbivores, the range of prey of predators or the pollination networks are to be expected

(Tylianakis, Didham, Bascompte, & Wardle, 2008; Schweiger et al., in prep.). This might generally result in drastic changes in the provision of services (Montoya & Raffaelli, 2010).

Among the regulating services most strongly related to biodiversity, pollination and biocontrol of pests have to be highlighted. Climate change tends to increase the abundance of pest species particularly in previously cooler climates, but assessments of changes in impacts are hard to make (SCHERM, 2004). Insect pests are directly influenced, e.g. through the quality of food plants (NIKLAUS, 2007) or via the effects on their natural enemies (predators and parasitoids). Direct impacts are via the relatively high temperature optima of insects, which lead to increased vitality and reproduction (PIK, 2005). Mild winters in temperate areas promote frost susceptible pests. For the vast majority of indirect effects, e.g. spread of insect borne diseases, information is scarce.

Pollination

Climate change, after land use changes, can be regarded as the second most relevant factor responsible for the decline of pollinators (S. G. Potts et al., 2010; for other factors see Biesmeijer et al., 2006; C. Brittain et al., 2010; C. A. Brittain, Vighi, Bommarco, Settele, & Potts, 2010; S. G. Potts, et al., 2010; S. G. R. Potts, S.P.M., Dean, Brown, Jones, & Settele, 2010). While the potential influence of climate change on pollination can be manifold (compare Hegland, Nielsen, Lazaro, Bjerknes, & Totland, 2009; Roberts et al., (in review); Schweiger et al., in prep.), there are only few observations which mostly relate to the de-coupling of plants and their pollinators – especially in relation to phenology (Gordo & Sanz, 2005).

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

It can be expected that the impacts of climate change on the main pollinator groups (bees and syrphid flies) show similar patterns like e.g. butterflies (Roberts, et al., (in review); J. Settele et al., 2008; Josef Settele et al., 2009). For butterflies it has been shown that drastic climate change effects can be expected under a set of future scenarios (Spangenberg et al., 2011, in press) and that only for few species rather positive effects can be assumed (while connectivity of the landscape and the mobility of species are important and widely unknown factors, which might drastically change the expected future impacts). While for the majority of species the climate space for the insect is limiting, there are species with particular dependence on certain plants which might suffer because of the different movements of future climatically suitable space of plants and butterflies (Schweiger et al., 2011, in press; Schweiger, Settele, Kudrna, Klotz, & Kuhn, 2008). As in butterflies the plants are largely independent from the insect in their development, one might expect more severe developments in tighter interacting pollination systems (absence of pollinator could mean absence of pollination dependent plant and vice versa; compare results of Biesmeijer, et al., 2006).

4.3.5.5. Climate Regulation Services

Terrestrial ecosystems affect climate through their influence on the physical properties of the land surface as well as through biogeochemical cycles. Observational and modelling evidence indicates that, broadly speaking, forests make warmer areas cool and colder areas warm, through competing effects of evapotranspiration and surface albedo. Changes in ecosystems, whether due to climate change or direct human influence, may therefore affect such ecosystem services to climate. Modelling studies such as (2007) suggest that Amazon deforestation above a threshold of approximately 40% could lead to reduced rainfall. (2011, Nature Geoscience) suggested that the overall effect of tropical afforestation on global temperature including evapotranspiration effects could be 1.75 times the effect expected on the basis of carbon sequestration alone. (2011) uses satellite data to infer that the biogeophysical effects of conversion of Brazilian cerrado to pasture were to induce a local warming, but this was partly offset by a further conversion to sugarcane. Singerayer and Bernard (Phil Trans R Soc, in review) suggest that "crop biogeoengineering" (planting high albedo crops) could contribute to climate change mitigation.

A modelling study by (2007), suggested that ozone damage may have weakened global vegetation growth historically and that this effect may increase in the future. This may have implications for mitigation.

(2010), examined the effect of ozone damage to vegetation as caused by anthropogenic emissions of ozone precursor species and quantify it in terms of its impact on terrestrial carbon stores. A simple climate model is then used to assess the expected changes in global surface temperature from the resulting perturbations to atmospheric concentrations of carbon dioxide, methane, and ozone. For NOx emissions, the longer-timescale methane perturbation is of the opposite sign to the perturbations in ozone and carbon dioxide, so NOx emissions are warming in the short term, but cooling in the long term. For volatile organic compound (VOC), CO, and methane emissions, all the terms are warming for an increase in emissions. The GTPs for the 20 year time horizon are strong functions of emission location, with a large component of the variability owing to the different vegetation responses on different continents.

Huntingford et al., (2011) demonstrated highly contrasting effects of different climate forcing agents on terrestrial ecosystem services when non-radiative impacts were also considered. Ozone effects lead to decreased NPP (which could be considered a first-order surrogate for food availability) but increased runoff (viz fresh water availability) CO2 effects led to increased NPP and again increased runoff

[Figure: global map of biome shift predictions from CMIP5.
Data starting to be available. Could do this for Hadley Model and Canadian Model already (both Earth System models with interactive vegetation) – will work on this.]

4.3.5.6. Tourism, Amenity

The tourism and recreation sector accounts for about xx% of global economic activity, and is growing at a higher rate than the global economy as a whole (refs). A significant portion the tourism and recreation activity is linked to ecosystems, directly or indirectly, making the sector sensitive to climate change. The direct links are through 'nature-based tourism', such as birdwatching, hiking, camping, hunting and fishing ('ecotourism' is a particularly socially- and environmentally-conscious subset (Ref)). The indirect dependence relates to the desire to have pleasant environments in which to relax – safe beaches, clean rivers and lakes, good snow conditions and a comfortable climate**. [more text to be added] [Reference to the work of Duan Biggs and others on tourism sensitivity to climate change]**

4.3.5.7. Water, including Quality and Groundwater

[to be elaborated]

4.4. Adaptation

4.4.1. Autonomous Adaptation by Ecosystems

4.4.1.1. Phenological and Physiological

Phenology refers to the timing of life-history events in plants or animals, which are typically highly adapted to the climate seasonality of the environment in which the organism evolved. The phenology of any species also needs to be keyed to the phenology of other species with which it interacts, such as competitors, food species and pollinators. Thus change in phenology is both a sensitive indicator of adaptation (?Menzel et al., 2006), but also a potential mechanism of ecosystem disruption if adaptation is insufficiently rapid or coordinated between interdependent species, or is cued to environmental signals that are not affected by climate change, such as day-length (Parmesan, 2006).

There is clear evidence of earlier leaf emergence and fruit set in the temperate and boreal ecosystems of the northern hemisphere, based on evidence from large networks of local observations (?Menzel, et al., 2006). The start of spring, by this metric, has advanced over the period 1971-2000 by 2.5 days/decade. In the same region, the time at which leaves change colour and fall has shown trends towards earlier and later dates with approximately equal frequency. Few systematic phenological observations exist for the tropics and southern hemisphere, so no trend have been detected. Averaged by country, which reduces the effect of spatial differences in sample density, the sensitivity of leaf colour change to temperature in the preceeding month is 1 day/°C.

A longer leafy period has consequences for the carbon cycle, the hydrological cycle, and the exchange of energy between the land surface and the atmosphere (Penuelas, Rutishauser, & Filella, 2009). But the environmental cues for phenological events are complex and multi-layered (Körner & Basler, 2010). For instance, late-succession temperate trees require a chilling period in winter, followed by a threshold in daylength, and only then are sensitive to temperature. As a result, projecting current phenological trends forward is risky, since the relative importance of cues can change. The results are sometimes counterintuitive, such as the increased sensitivity of flowering in high-altitude perennial herbs in the Rocky mountains to frost as a result of earlier snowmelt (Inouye, 2008).

[Further text here. See also Rosenzweig et al 2008, McMahon SM, GG Parker, and DR Miller 2010]

The mean dates of arrival of migratory birds in Europe has become earlier by up to one day per year over the period 1970-2000 (Moller, Rubolini, & Lehikoinen, 2008). This effect remained statistically significant even after many other factors known or hypothesized to have an effect on the migration date were accounted for. Furthermore, the species that did not adjust their arrival date on average showed declining populations, while those that advanced their arrival showed stable or increasing populations citation.

Satellite-based measurements of the date of greening in the northern hemisphere (Zhou et al., 2001) show earlier onset and later leaf fall. Spatially-coherent, statistically-significant trends in the annual sums of satellite-derived vegetation indices (which includes changes in both the duration of the growing season, and the peak leaf area reached) have been detected in many parts of the world – particularly the drylands – and in many studies (refs). The trends are often attributed to changes in rainfall, and once the effect of rainfall has been removed, to human-induced desertification or recovery (refs). The areas that are identified as having become more or less green do not correspond in different studies. The diagreements may be due to methodological differences, such as the use of different satellite sensors, vegetation indices, and trend detection methods. The relatively short duration of satellite observations makes trend detection particularly sensitive to the choice of analysis period.

The physiological processes in organisms can either adapt phenotypically or genetically (ie, through evolution). The former is generally regarded as rapid but limited, and the latter as less constrained, but slow (see 4.4.1.3). A key physiological adaptation with large potential consequences for the global climate system is the sensitivity of the relationship between organism temperature and respiration rate, particularly in decomposer organisms (C. D. Jones, Cox, & Huntingford, 2003). The shape of the relationship varies between locations with different climates and shows apparent acclimation within months or years to a changing climate (Giardina & Ryan, 2000, ?Rustad, 2001). The relationship is also dependent on C substrate type and the presence of other respiration-controlling environmental factors, complicating the determination of the inherent rate and its adaptation to a changing climate. Several competing hypotheses can explain the observed reduction in respiration rates in soil warming experiments after an initial peak – physiological adaptation (); depletion of readily available substrate (Kirschbaum, 2004); and varying temperature sensitivities in different soil carbon pools (Knorr, Prentice, House, & Holland, 2005).

In carbon cycle models the relationship is widely assumed to be exponential in form, with an approximate doubling in the rate for every 10°C temperature rise (Q10 ~2, although there is no theoretical reason why this must be so, and empirically-measured rates are both higher and lower: Davidson & Janssens, 2006). In consequence, the models predict large future increases in respiration (leading to a reduction or even a disappearance of the land carbon sink) as the world warms. The amplitude of the contemporary interannual variation in atmospheric CO2 constrains the globally-integrated Q10 to the range 2.1 + 0.1. A recent compilation of 1434 soil respiration measurements, widely but imperfectly distributed from terrestrial ecosystems around the world (Bond-Lamberty & Thomson, 2010), showed an increase in soil respiration of 0.1 PgC y-1 over the period 1989 to 2008, corresponding to a global Q10 of 1.5. Some of this increase could be due to increasing inputs of carbon into the soil as a result of increased primary productivity.

Climate change-mediated changes in the soil environment – for instance, the thawing of permafrost – may ultimately be more important in controlling the rate of soil respiration than direct temperature responses.

4.4.1.2. Compositional and Structural

Changing species abundances, species losses and gains and phenology can lead to structural and compositional changes of natural and experimental species communities and ecosystems at a taxonomical, functional level and phylogenetic level. Compositions change often towards more warm and drought tolerant species and traits (e.g. tropical forests in Panama, Feeley, et al., 2011; temperate steppe in China). Although projections of does not show a higher loss of evolutionary history (i.e. phylogenetic diversity) than expected by chance, the projected losses will lead to phylogenetic homogenization across European plant, bird and mammal communities.
Biotic interactions such as pollination or predator-prey networks can be disrupted due to decoupling of range overlaps as future projections show for a butterfly-plant pollination system or due to decoupling of predator-prey systems as observations on the edible dormouse and the pied flycatcher shows ().

4.4.1.3. Evolutionary and Genetic

There is increasing evidence that species have adapted to recent climate warming or to climatic extremes through rapid evolution (Chown et al., 2010; Franks & Weis, 2008; Hoffmann & Sgro, 2011; Karell, Ahola, Karstinen, Valkama, & Brommer, 2011; Ozgul et al., 2010). Rapid evolution can occur through many mechanisms including selection of existing resistant genotypes within populations, mutation and selection of new genes and perhaps even through epigenetic processes such as DNA methylation (Lavergne, Mouquet, Thuiller, & Ronce, 2010, Paun et al., 2010). Most evidence for rapid evolution comes from species with rapid life cycles; however, even long-lived species such as trees may adapt to some extent over the coming century through selection of resistant genotypes (Kramer et al., 2010). Rapid evolution could save species from local and global extinction, i.e., "evolutionary rescue", but at the price of substantial loss in genetic variability and reductions in populations size if the impact of climate on populations is severe (Urban et al., 2008, ?Bell & Gonzalez, 2009, Leadley et al. in prep).

It has been argued that rapid evolutionary responses are of little importance in the face of climate change (Parmesan, 2006). Evidence from the fossil record clearly shows that range shifts and other non-evolutionary responses dominate the long-term response of species to climate change, suggesting that adapation is of minor importance (Schoener, 2011). However, evolutionary reponses may have buffered such range shifts (M. B. Davis, Shaw, & Etterson, 2005; Warren et al., 2011) and, most importantly, rapid adaptation may prevent species extinctions (?Bell & Gonzalez, 2009).

Rapid advances in quantitative genetics, genomics and phylogenetics have provided valuable insights into the functional importance of genetic variability within populations and among species (C. C. Davis, Willis, Primack, & Miller-Rushing, 2010; Salamin, Wuest, Lavergne, Thuiller, & Pearman, 2010, Hoffmann & Sgro, 2011). For example, the timing of budburst in trees has been shown to be under partial genetic control and to be one of the important adaptive responses of trees to climate (Vitasse, Delzon, Bresson, Michalet, & Kremer, 2009). Studies of extent genetic variability across species ranges and with models that couple gene flow with spatially-explicit population dynamics suggest that populations are equally sensitive to climate change in ways that are counterintuitive. In some cases, too much or too little gene flow to populations at range margins may have created fragile, maladapted populations, which is in contrast to the current wisdom that equatorial populations may be best adapted to global warming (Bridle et al. 2008). Conversely, there is also evidence from experiments, models and observations that populations in the center of species ranges may in some cases be more sensitive to environmental change than those at range boundaries (Gonzalez et al. in prep). Generalization will be complicated by the complex interactions between local adaptation, gene flow and population dynamics (Leadley et al., in prep).

4.4.2. Human-Assisted Adaptation

4.4.2.1. Reduction of Non-Climate Stresses

[in progress]

4.4.2.2. Adaptive Management

[Note – italics indicates findings that could be used or recast for the Exec Summary]

The large magnitude, rate and uncertainty of on-going and future terrestrial change has prompted rapid development of adaptive management and/or governance, wherein decisions are made within the range of existing uncertainty, progress is monitored, and new decisions evolve to adjust to learned outcomes, new knowledge, and other information (Folke, et al., 2004; Gunderson & Light, 2006); ?Allen, Fontaine, Pope, & Garmestani, 2011). Adaptive management has been applied across a range of applications, and has even been advocated in legal decision-making with respect to climate change (e.g., C. Allan & Curtis, 2005; Brickey et al., 2010). At the same time, successful adaptive management has been limited in many cases because of: (1) poor ecological understanding (often social- as well as natural-science), (2) lack of shared vision, trust and flexibility among diverse decision-makers (“stakeholders”), (3) inadequate provision for conflict-resolution, (4) insufficient commitment for the design and execution of often complex adaptive management strategies, (5) not enough monitoring or experimental capability, (6) an unwillingness (or inability) of managers to makes decisions given inherent uncertainty, risk, and possible surprise, and (7) other factors (Allen & Gunderson, 2011; Feldman, 2008; Folke, Hahn, Olsson, & Norberg, 2005; Gregory, Ohlson, & Arvai, 2006; Walters, 2007). *There is little doubt, however, that the inherently changing and improving knowledge about human-caused terrestrial change, often with respect to local geographies and issues, necessitates management strategies that embrace uncertainty, are informed by diverse scenarios and scenario planning, allow for risk-taking, build on stakeholder-scientist partnership, learn from theory, experiments and practice, and adjust iteratively in time* (e.g., Allen & Gunderson, 2011; Baron et al., 2009; Peterson, Cumming, & Carpenter, 2003; Rout, Hauser, & Possingham, 2009).

4.4.2.3. Protected Areas: Amount, Location, and Layout

Additions to, or reconfigurations of, the protected area estate are commonly suggested as pre-adaptations to projected climate changes (Heller & 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 current protected area footprint. It is noted that the current geography of protected areas is far from optimal under the current climate, and that it is cheaper to proactively acquire land in the areas of likely 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). The amount of new area that needs to be added it 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 purely local scale (Heller & Zavaleta, 2009); and better integration with a biodiversity-hospitable landscape outside the protected area is more effective than treating the protected areas as islands.

4.4.2.4. Landscape and Watershed Management

When fragmentation limits migration potential of many species or when natural migration rates are outstripped by the pace of climate change, human-mediated migration (assisted migration) is proposed as a solution (Chmura et al., 2011; Vitt, Havens, Kramer, Sollenberger, & Yates, 2010). In the northwestern U.S., warmer temperatures and changed precipitation predispose forests to disturbance by wildfire, insects, and disease; and ultimately change forest structure and composition at the landscape scale. In this area, effective approaches to climate adaptation will likely include assisted migration of species and populations, and density management (Chmura, et al., 2011). An example of grassland ecosystem is the framework currently being used by the Dixon National Tallgrass Prairie Seed Bank. It consists in the prioritization of species for seed banking, both for restoration purposes and for potential assisted migration in the future (Vitt, et al., 2010). A genome scan approach identified four potentially adaptive loci in important grassland species (*Arrhenatherum elatius)*. Knowledge on adaptive loci might in the long run also help to adapt ecosystems to adverse climate change effects through assisted migration of ecotypes rather than introduction of new species Michalski et al., 2010).

4.4.2.5. Assisted Migration and Restoration

Assisted migration and habitat restoration are receiving growing attention as a potentially necessary mesure to conserve species in the face of climate change (Hoegh-Guldberg et al., 2008; Loss, Terwilliger, & Peterson, 2011). However, the scientific community is strongly divided over whether it is best to increase the reslience of ecosystems to climate change, thus help to preserve existing communities, or to enhance the capacity of ecosystems to transform in the face of overwhelming forces of species migrations and modifications of ecosystem function by climate change. The options for management can be summarized in three main catagories: i) try to maintain / improve existing habitat so that species don't have to move, ii) maintain or improve migration cooridors, or iii) intervene heavily by translocating species (Hoegh-Guldberg, et al., 2008, Loss, et al., 2011).

Maintaining or improving migration coorridors or ecological networks has relatively broad support from the scientific and conservation community, in large part because the measures required for reducing climate change impacts on species are also seen as useful in combatting the negative effects of habitat fragmentation on population dynamics (CBD ref, Hole et al., 2011, Jongmann et al. 2011). This approach has the benefit of improving the migration potential for large numbers of species and, therefore, is a more ecosystemic approach that assisted species migration. Some caution should be excercised because observational and modeling studies show that increases in habitat connectivity do not always improve population dynamics of target species, may decrease species diversity, and facilitate spread of invasive species (Cadotte 2006, Brisson et al. 2010, Matthiessen et al. 2010).

Assisted migration is in contrast a highly controversial. A growing number of ecologists see assisted migration as an important means of overcoming migration limitations to species response to climate change (Hoegh-Guldberg, et al., 2008, Loss, et al., 2011, Vitt et al. 2009, Willis et al. 2009). The speed of 21st century climate change and substantial habitat fragmentation in many areas of the world mean that many species will be unable to migrate fast enough to keep pace with climate change. If this results in significant reductions in range size this is likely pose problems for long-term survival of the species. Moving species may help overcome migration limitations, but raises serious issues about introducing species into ecosystems where they do not currently occur. Some ecologists believe that careful selection of species would minimize the risk of undesirable impacts on existing communities or ecosytem function (Minteer & Collins, 2010), but others argue that the history of intentional species introductions shows that the outcomes are often unpredictable and in many cases have had disasterous impacts (?Ricciardi & Simberloff, 2009). An additional issue is the number of species that could potentially require assisted migration that could easily overwhelm funding capacity.

4.4.2.6. Ex Situ Conservation

Conservation of plant and animal genetic resources outside of their natural environment, in gardens, zoos, breeding programmes, seed-banks or gene-banks has been widely advocated as an ‘insurance’ against both climate change and other sources of biodiversity loss and impoverishment (Khoury, Laliberte, & Guarino, 2010). There are many examples of existing efforts of this type, some very large and with global scope (Millennium Seed Bank, Svalbard vault etc). It is estimated that xx% of global plant species are under some form of ex situ conservation (Ref). Several issues remain largely unresolved (Li & Pritchard, 2009): the physiological, institutional and economic sustainability of such efforts into the indefinite future (Refs); the fraction of the intra-specific variation that is preserved (and how much needs to be preserved for future viability) (Refs); and whether it is possible to reintroduce such species (especially animals) successfully into the wild after generations of ex-situ conservation (Refs).

4.4.3. Barriers, Limits, and Incentives to Adaptation

The autonomous adaptation of wild organisms to climate change relies heavily on the capacity to migrate to areas of suitable climate. Even for those organisms theoretically capable of doing so at the required rate (Ref Midgely, Foden), physical barriers often prevent their movement. These can be topographic (eg valleys, mountain ranges and water bodies), but are increasingly human-created, such as fences, roads and areas of unsuitable habitat (such as croplands or settled areas) (Ref). Increasing habitat fragmentation reduces the pathways that a migrating organism can take (Ref).

Organisms can also adapt physiologically or evolutionarily. There are some limits to either the rate or the magnitude of such adaptations. There are apparently upper temperature limits to the setting of seed in many grasses (ref).

[Incentives?]

4.4.4. Consequences and Costs of Inaction and Benefits of Action

[We have collected material; actually that is what TEEB was all about and we are presently trying to summarize the main elements in just a few words (we will then need a contributing author from the field in the near future)]

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

[in progress]

4.5. Emerging Issues and Key Uncertainties

An issue that emerged in the fourth Assessment Report and has grown substantially in prominence since then is that of thresholds, and specifically the type of thresholds characterised as ‘tipping points’. These represent the point at which positive feedback processes dominate over negative feedback loops, and the system begins to change as a result of both its internal dynamics and the external forcings, leading to a change in state that is difficult or slow to reverse (Refs). Ecosystems, with their high degree of connectivity, typically non-linear interactions and prevalence of time-lags, are likely to exhibit this type of ‘resistance followed by abrupt change’ behaviour when forced. Many examples of such thresholds have now been identified (refs). Most are at the local scale, but the potential existence of ecological thresholds at a sufficient scale to have regional or global consequences is high. Posited examples include a drought and temperature threshold in the Amazon, beyond which fire and respiration lead to a quasi-irreversible loss of carbon (Cox et al), and thawing of permafrost (Ref), leading to emissions of CH_4 and CO_2 in sufficient quantities to further warm the Earth and amplify the permafrost warming. In general (C. B. Field, Lobell, Peters, & Chiariello, 2007), negative feedbacks currently dominate, but in boreal zones positive feedbacks could dominate under moderate warming. For positive feedbacks to propagate into a ‘runaway’ process leading to a new equilibrium state, the strength of the feedback has to exceed that of the initial perturbation. This has not been demonstrated for any plausible and immanent large-scale ecological process as yet, but for most processes increasing degrees of warming tip the balance towards positive rather than negative feedbacks (C. B. Field, et al., 2007).

A significant source of uncertainty in ecological responses 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 understanding the systems better, but some will remain irreducible because of the failure of predictive models when faced with mathematical bifurcations – a problem that is well-known in climate science. Probabilistic statements about possible outcomes are theoretically possible in this context, but ecosystem science is far from being able to conduct such analyses routinely.

4.6. Frequently Asked Questions

How many species will become extinct?

To be answered

Why do ecosystems matter?

To be answered

Will the Amazon be lost?

Some climate projections suggest severe impacts in Amazonia if emissions follow “business-as-usual” scenarios (Cox, Betts, Jones, Spall, & Totterdell, 2000; Salazar, Nobre, & Oyama, 2007), and indeed even if global climate change is stabilised at relatively low levels (C. Jones, Lowe, Liddicoat, & Betts, 2009). However, although most of the AR4 climate models simulate some level of future drying in Amazonia, in most cases this does not take the climate past thresholds thought to be important for the viability of rainforest (?Malhi, et al., 2009). The key uncertainties in the “Amazon die-back” projection appear to be the SST responses to climate change, and strength of CO2 fertilization in offsetting climate effects. While strong carbon cycle feedbacks help explain the extreme result in one model (Cox, et al., 2000), and indeed AR4 models may underestimate warming and hence regional climate change by using CO2 concentrations from a model with relative weak carbon cycle feedbacks, this is not a key factor in whether die-back occurs to some extent. As far as plant physiological impacts are concerned, lower levels of global warming could lead to die-back if the necessary SST changes occur, especially if CO2 fertilization is weak. Overall, then, there remains large uncertainty in the projected regional climate change in Amazonia due to ongoing GHG emissions. A majority of AR4 climate models project some reduction in precipitation in some parts of the basin in some seasons, and the model with the most severe regional climate response to warming also happens to be the only model to date that incorporates both global and local ecosystem feedbacks which magnify this regional climate response [NB This statement will need to be revised in the light of AR5 model results] [Also NB New Hadley model HadGEM2-ES *does not* produce Amazon dieback!!]. On the basis of multi-model evidence, severe warming and drying leading to forest die-back does not appear to be the most likely scenario, but cannot be ruled out.

However, a key issue is the interaction between climate change and land use. Forest fragmentation reduces the resilience of the forest, because fires are more frequent near forest edges and a fragmented forest contains more edges than a pristine forest (Cochrane, 2001; Cochrane & Laurance, 2002; Laurance, 2004; Alencar et al., 2004), thus forest fire frequency in Amazonia would be expected to increase as a result of forest degradation even in the absence of climate change. This could be further enhanced by a drying climate. With the sensitivity of the Amazonian forests to dry conditions increased by further fragmentation, disturbance by logging (Asner et al., 2005), and recurrent fires (?D. Nepstad et al., 2001), this may lead to greater impacts on the forest than would be expected for a pristine forest. A scenario of an intermediate level of drying (as opposed to severe drying) may not imply direct impacts on forest cover through the plant physiological responses to climate, but it may exert impacts through fire if the forest is fragmented.

[NB HadGEM2-ES does not include fire…]

Under the moderate drying scenarios, reduced deforestation may therefore play a role in conserving a wider area of forest than that immediately threatened by the deforestation. Reduced deforestation would therefore not only reduce emissions from the area directly subject to potential deforestation, it would also reduce the risk of further emissions from neighbouring non-deforested but less resilient forest areas, by decreasing the risk of fire through removal of the ignition source.

[INSERT FIGURE 4-11 HERE
Possible Figure 4-11: Map showing multi-model projections of change in fire danger (meteorologically defined), overlaid with projection(s) of deforestation. [The example attached shows this for a 17-member ensemble of variants of the HadCM3 climate model using the McArthur Forest Fire Danger Index (Golding & Betts, 2008) and the Soares-Filho (2004) Bussiness-As-Usual projection deforestation projection. Will need to revise this in the light of more recent projections]

What are the non-GHG effects of CO_2?
To be answered

What are the positive effects of climate change on ecosystem services?
To be answered

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Table 4-1: See the Excel work sheets within <WGIIAR5-Chap4_ZODtab4-1.xls>.

Table 4-2: Sources of information on observed ecosystem change.

Information type	**Methods**	**Length of records**	**Geographical coverage**	**Key conclusions**	**Uncertainties / difficulties**	**Level Of Scientific Uncerstanding*** NB statements below are only my personal suggestions – discussion welcome!
Phenological records	Recording dates of key events in seasonal cycle of life forms	1920s (Mohonk Lake, NY) 1700s (eastern England)	Large number of site-specific records, mainly in Europe and North America but some elsewhere	A variety of different trends in dates of key phonological events (bud burst, date of first sighting) are seen in the records. For plant species there is a predominance of sping-onset dates occurring earlier, but this is not universal. Some species show no trend or an opposite trend. In a given location, trends for different species may be very different.	Breaks in record, changes of observer, changes in definition, changes in location	High?
Dendro-chronology		Centuries	Large number of site-specific records, largely in high latitudes		Obtaining representative sample Sites often chosen for value as indicators of environmental change not specifically ecosystem monitoring.	Medium *(NB: as indicator of vegetation change – use as climate proxies is out of scope here)*
Tree biomass measurement	Measure tree trunk circumference at a standard reference height and convert to biomass estimate	Approx 20 years	Several dozen sites throughout tropics (not sure about sites outside tropics yet)	General trend of increasing biomass, but with some short-lived losses e.g.: drought events in Amazonia	Obtaining representative sample, accessing sites for repeat measurements	Medium-low? (Much fewer studies / papers than phenology or dendrochronology
Species counts (is this the right way to describe it?)	Species counts in well-defined plots (often small) or transects	Approx 20 years?	Sites worldwide exist, but don't yet have full picture of coverege?	Changes in number of species observed at specific sites**		Low?
Earth Observation by satellite	Measure differences in outgoing radiation from Earth, and use to infer changes in the character of the surface. Eg: Normalised Difference Vegetation Index (NDV) is the difference	1982-…	Global (mostly..) (specify spatial resolution?) Different levels of confidence in different areas, eg; due to cloud / snow contamination	General increase in vegetation "greenness" but with local / regional exceptions, especially in more recent years	Changes of instrument (e.g.: AVHRR to MODIS)	Low?

	between 2 infra-red wavebands					
Flux measurements	CO_2, H_2O	Approx 20 years?	Site-specific measurement in most major biomes			Low?
River and stream gauging stations	Measure river height / speed and covert to flow rates using local calibration	Several decades	Records in most major rivers worldwide (?)	General trend o increasing streamflows at high latitude, decreasing flows at low latitudes	Accounting for direct anthropogenicv interference	Low?

* potentially useful to try to make a judgement on "Level Of Scientific Understanding" (LOSU) as done in WG1. These needs to have some kind of quantitative basis, at least in a relative sense. In the radiative forcing chapter we made a 2-D matrix of "number of studies" and "agreement amongst studies", so that scoring high in each gave a relatively high LOSU and vice versa.

** Plot / site level data mostly tell us about changes in specieas composition in communities (mostly plants); longest records are reasonably old in NA and Europe (e.g., forest inventory, phytosociology relevees, etc.); problems involve lack of continuous records, probs with revisiting old sites, etc.); these data tell use that species composition is changing in a direction that is coherent with CC. Good metaanlysis in Parmesan and Yohe, but was severally lacking in vegetation measurements. This has improved substantially since the AR4 (Walther several refs, Lenoir, et al 2008, Damchen et al. 2010, etc.).

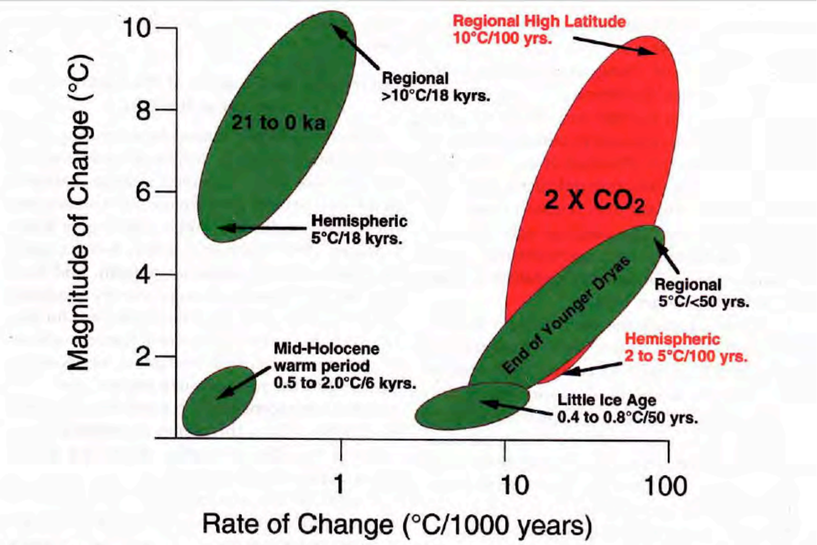
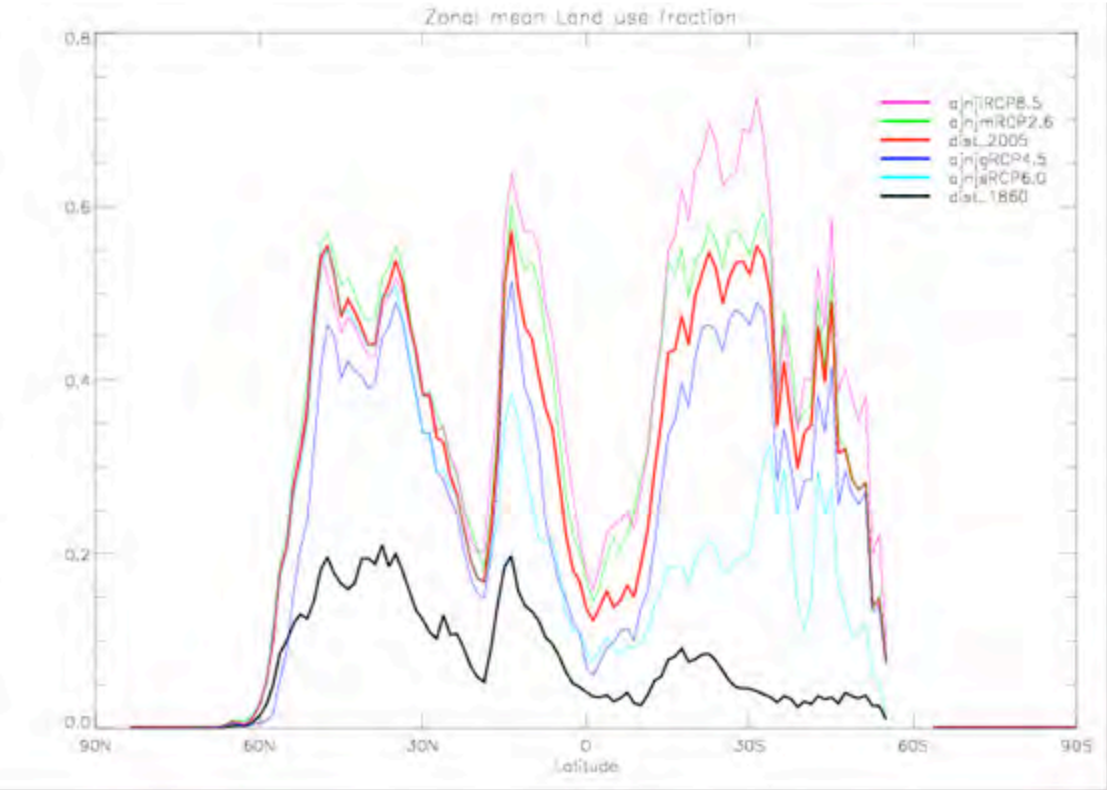
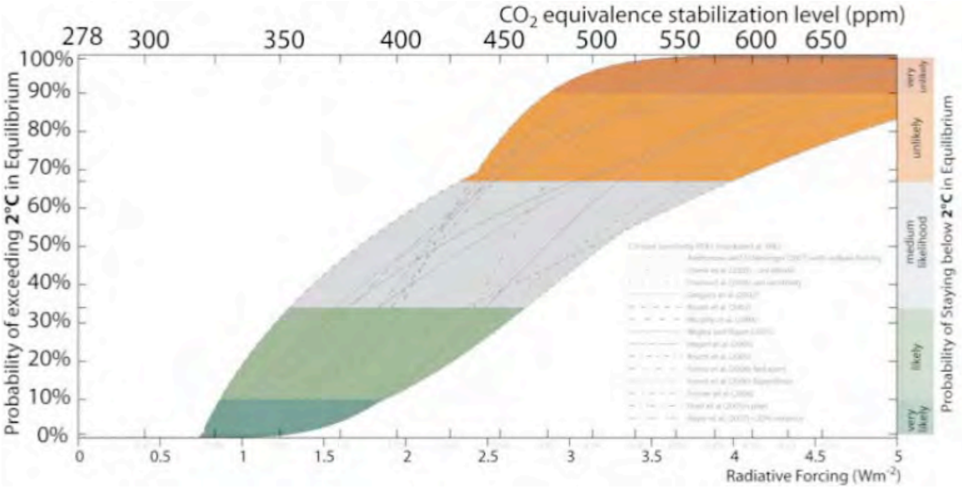


FIGURE 12. Summary comparison of the rates and magnitudes of possible future climate change (estimated in terms of mean annual temperature) with those associated with several well-known periods of past change in regions that were vegetated. Rates of future regional temperature change could far exceed any widespread change in the late Quaternary. See text for sources, and note that the estimated warming associated with the end of the "Little Ice Age" is currently estimated to be about half of the warming observed over the last 150 years (Overpeck et al. 1997; Mann et al. 1999, 2000).

Possible Figure 4-1 – to highlight the unprecedented nature of future climate change. Update/modify the figure at right (Stephen T. Jackson & Overpeck, 2000), to include the paleoclimatic events mentioned in text. Only focus on range of estimated global change – e.g., with box/wiskers. Color code them to indicate the extent to which extinctions or other ecological changes (e.g., large-scale biome shifts) were associated)



Possible Figure 4-2: Zonal mean anthropogenic land use fraction in CMIP5 simulations [this is from the HadGEM2-ES Earth System Model as an illustration]



Possible Figure 4-3: Probability of exceeding 2°C global warming for different CO2 concentration stabilisation level. Use this (or similar plot) to illustrate relationships between CO2 and warming assumed in ecosystem impacts studies – plot individual studies on this chart.

Possible Section 3.4.2 Figures

[labeled Figures 4-4 thru 4-8 to facilitate Comments collection]

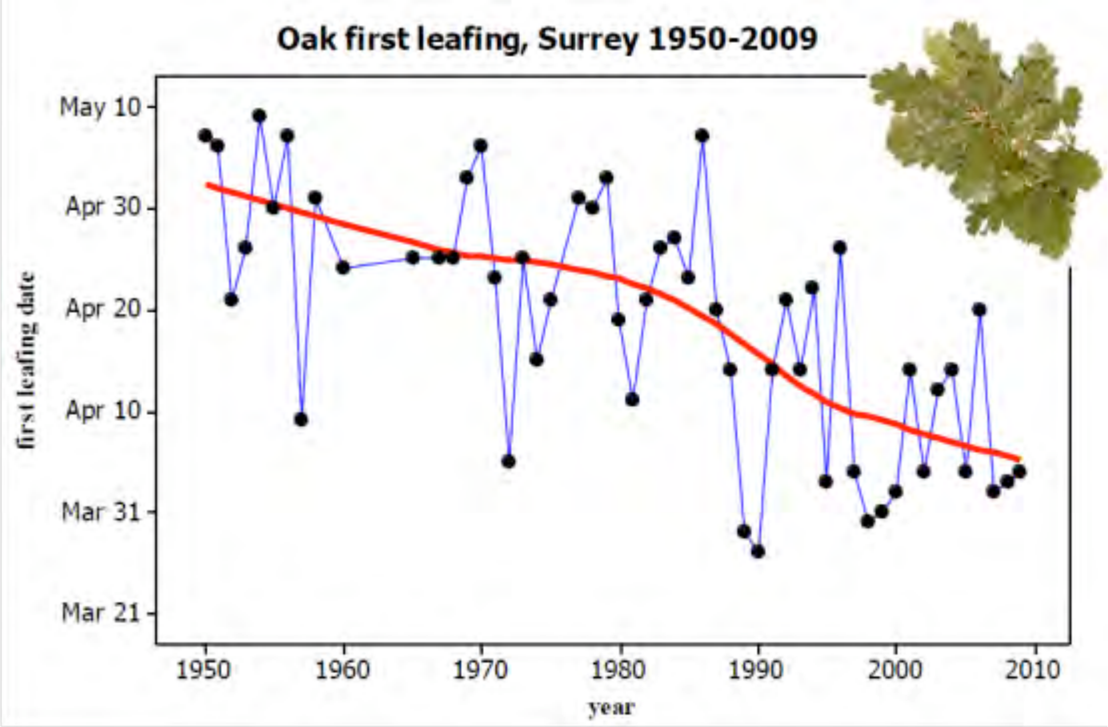


Figure 4-4
Source: pdf of Tim Sparks' presentation on UK Phenology network – need to enquire about paper / report

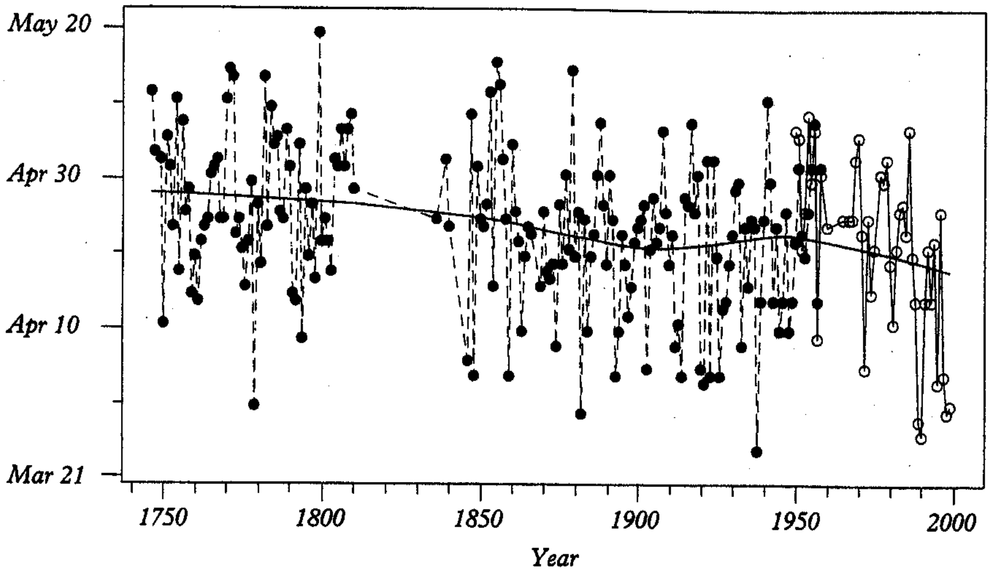


Figure 4-5: English oaks leafing dates: (Sparks & Carey, 1995).
[Longest phenological record I could find in literature so far – need to see if this is in any more recent papers with further analysis or other data for context)]

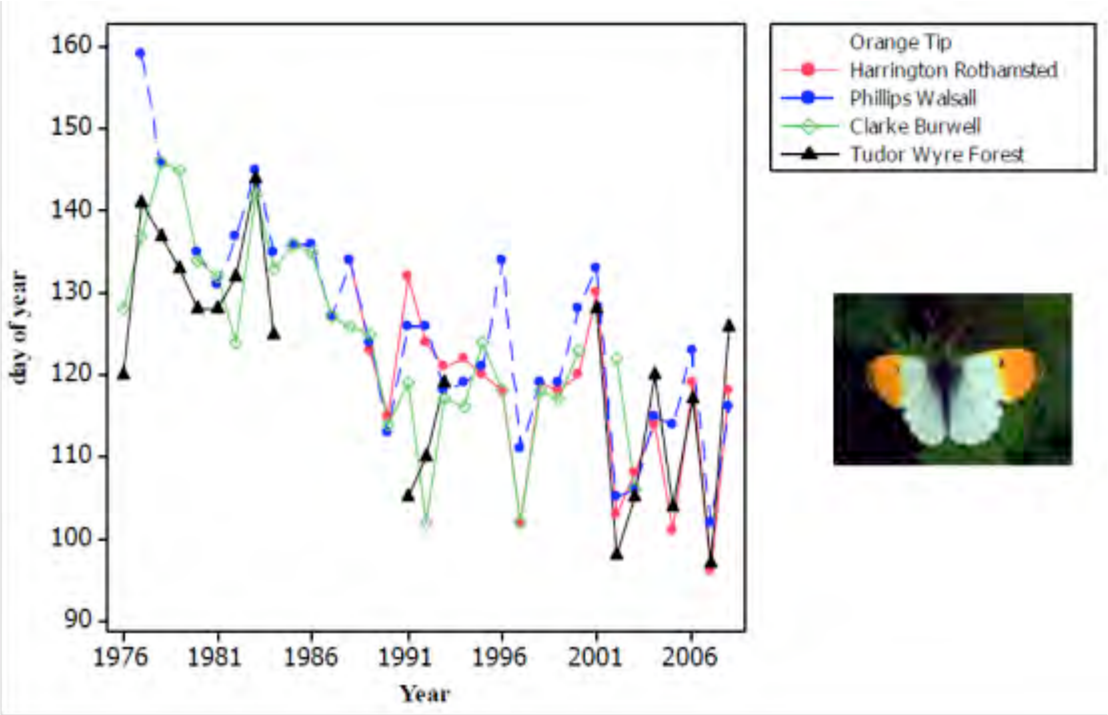


Figure 4-6
Source: pdf of Tim Sparks' presentation on UK Phenology network – need to enquire about paper / report

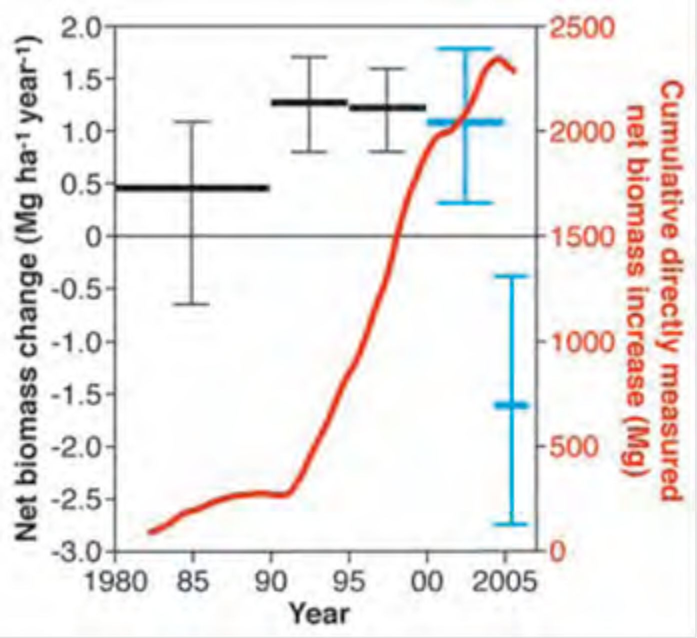


Figure 4-7
Interval-by-interval, plot-by-plot net biomass change measured in Amazonia between 1980 and 2005 (Phillips et al., 2009).

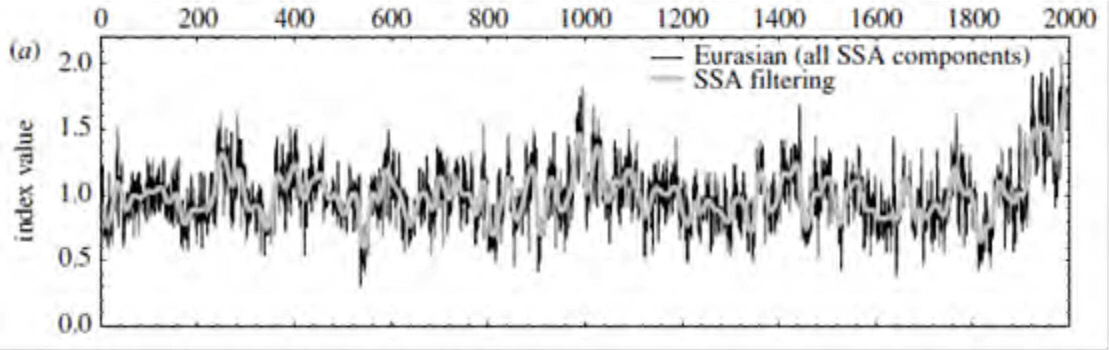
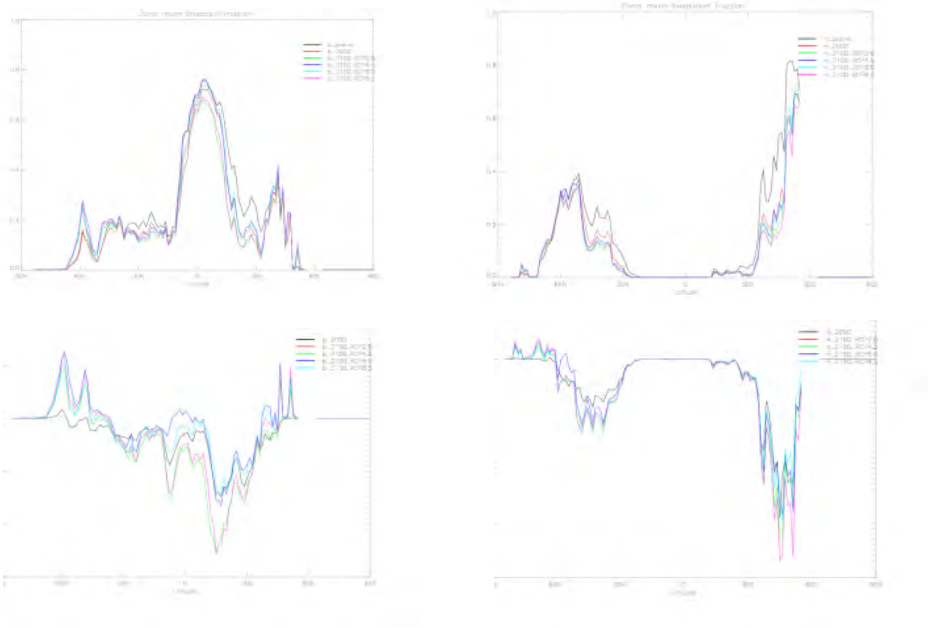
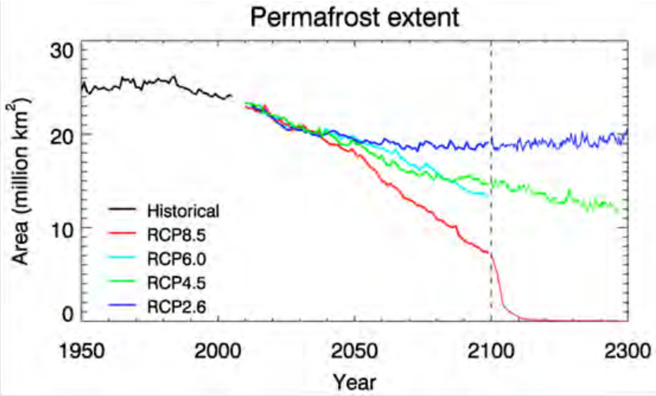


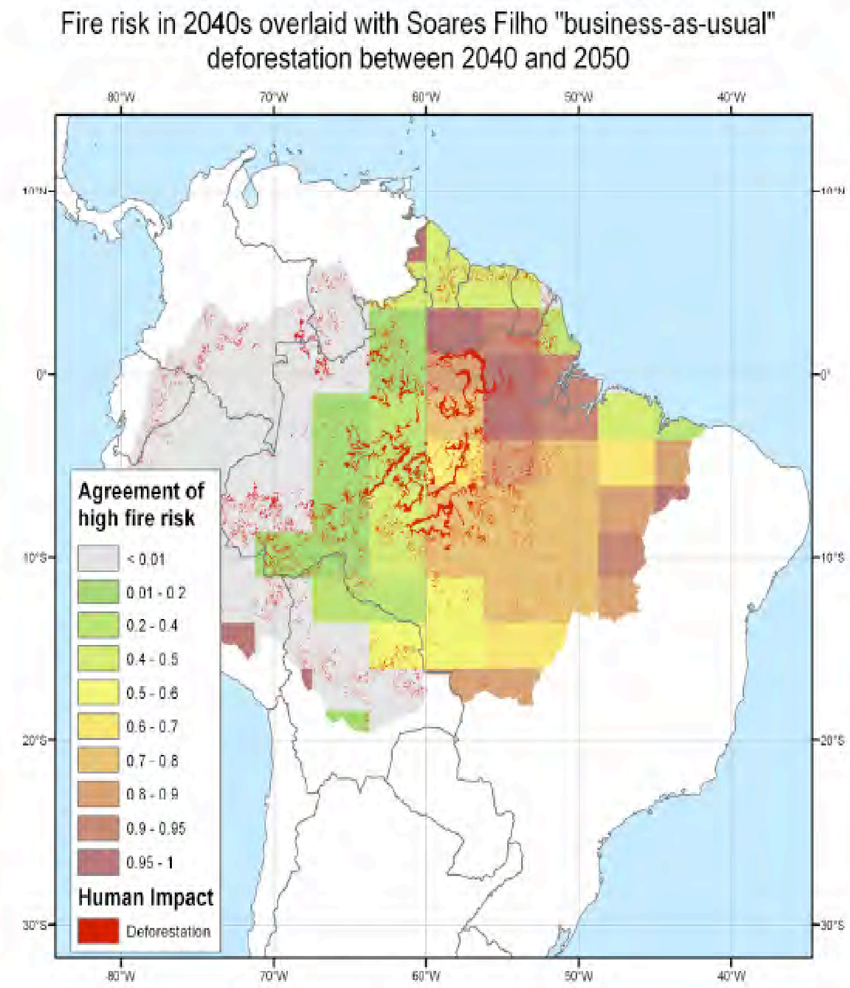
Figure 4-8
Tree rings: the regional curve standardized (RCS) northwest Eurasian chronology (thin lines) and the same chronology smoothed (thick lines; Briffa et al., 2008).



Possible Figure 4-9: Changes in zonal mean tree cover. **[This figure shows all latitudes but it may be appropriate to just show boreal forests]**. Zonal mean coverage of broadleaf (left) and needleleaf (right) trees, showing absolute values simulated for 2000 and 2100 (top) and the difference between 2100 and 2000 (bottom) for 4 RCP scenarios with the HadGEM2-ES ESM. **[Key point to make here is that the poleward expansion of boreal forests in general and both PFTs in particular can be seen on the left hand side of the plots, with NL trees expanding at northern latitudes but being replaced by BL trees at the southern side of the boreal zone. However NB this model does not include fire]**



Possible Figure 4-10: Historical observations and projections of the northern hemisphere permafrost area with a maximum thaw depth less than 3m deep. Projections are for the 4 main RCP projections from the HadGEM2-ES Earth System Model (Jones et al, submitted). Note x-axis scale change after 2100**. [NB not published yet, this is just preliminary results as a heads-up and to act as a placeholder. We currently think that the model overestimates the permafrost area.]**



Possible Figure 4-11: Map showing multi-model projections of change in fire danger (meteorologically defined), overlaid with projection(s) of deforestation. **[The example attached shows this for a 17-member ensemble of variants of the HadCM3 climate model using the McArthur Forest Fire Danger Index (Golding & Betts, 2008) and the Soares-Filho (2004) Bussiness-As-Usual projection deforestation projection. Will need to revise this in the light of more recent projections]**

OTHER FIGURES UNDER CONSIDERATION

Rates of migration figure

Figure on dynamics from boreal intercomparison

Figure on effects of having fire in or out of models

Note: There is boreal migration model comparison, as well as a fire model comparison being put together for Southern Africa (DIVERSITAS, GLP). I hope we will have the results for this in time. If the full blown study is not published, we can use individuals studies to illustrate two key points: i) boreal forest invasion of tundra is likely to be limited significantly by migration rates and ii) fire will dominate the response of many savanna ecosystems to climate change, but there is very high uncertainty in fire model projections. - PL

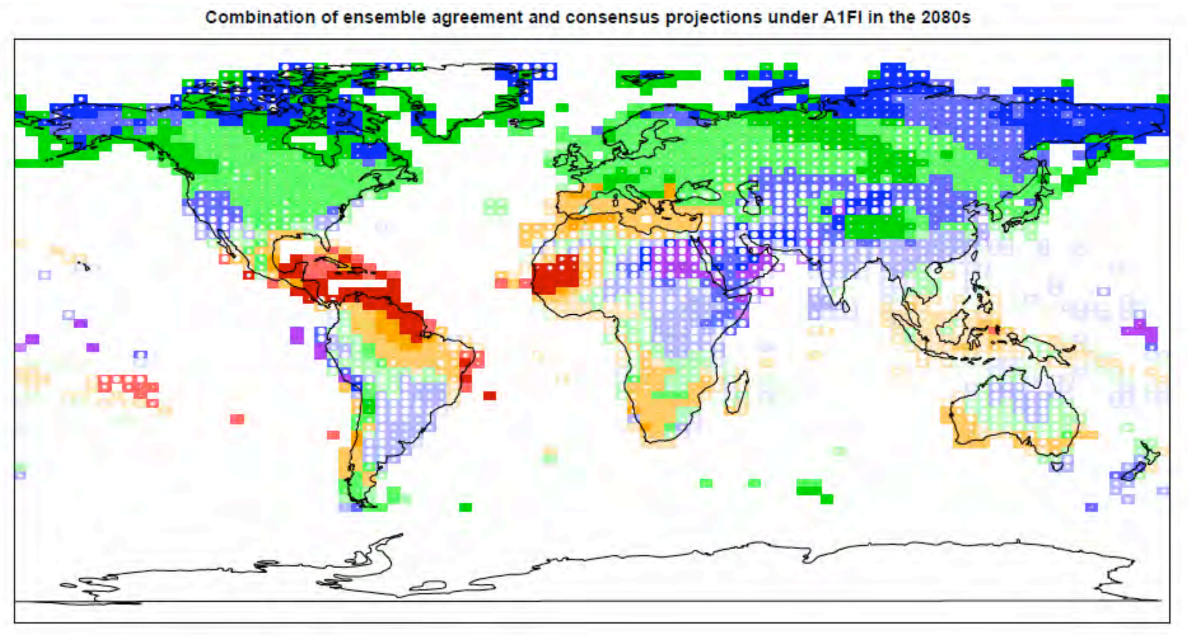
Bio

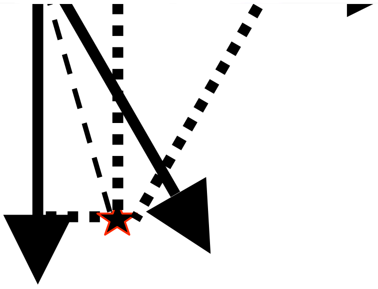
Figure on climate modelling study of one or more of the palaeo events

(Further thought: is there a suitable climate modeling study of one or more of the palaeo events discussed by JO, which could be expressed in these terms? However this may require a whole new piece of work!]

Figure quantifying uncertainty in climate change projections from the perspective of terrestrial ecosystems

Projected changes in an ecosystem-relevant "climate space" by the 2080s under SRES A1FI scenario, using CMIP3 multi-model ensemble. Colours in map show both the nature of the consensus change (warmer and drier / warmer & wetter), intensity of colour shows magnitude of consensus change as quantified in terms of movement in a Euclidian distance in a "climate space" (lower 2 panels), and size of white circles shows percentage agreement between climate models. Source: Hartley, 2011. NB this is for CMIP3 models – could repeat for CMIP5. Also this is for one scenario only (SRES A1FI – fastest warming) – could do for 2 or more RCPs to show difference between highest emissions (RCP8.5) and lowest (RCP 2.6).





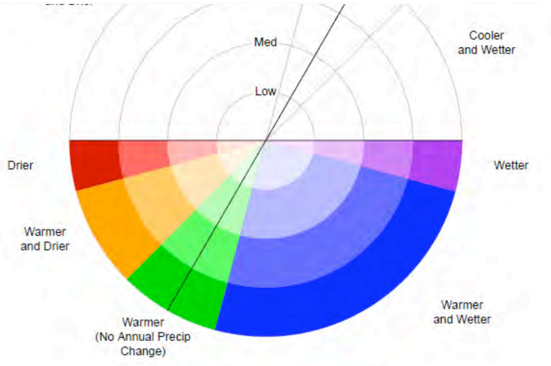


Figure quantifying uncertainty in climate change projections (box and whisker plot)
The box and whisker plot below shows the agreement on the projected Euclidian distance moved in “climate space” defined by Holdridge life zones for a 58-member GCM ensemble (this time the HadCM3C model) for the SRES A1B scenario. Currently this has been done for selected countries but this is only an example – it could be done for more ecosystem-based regions / major biomes, and for the AR5 multi-model ensemble when available.

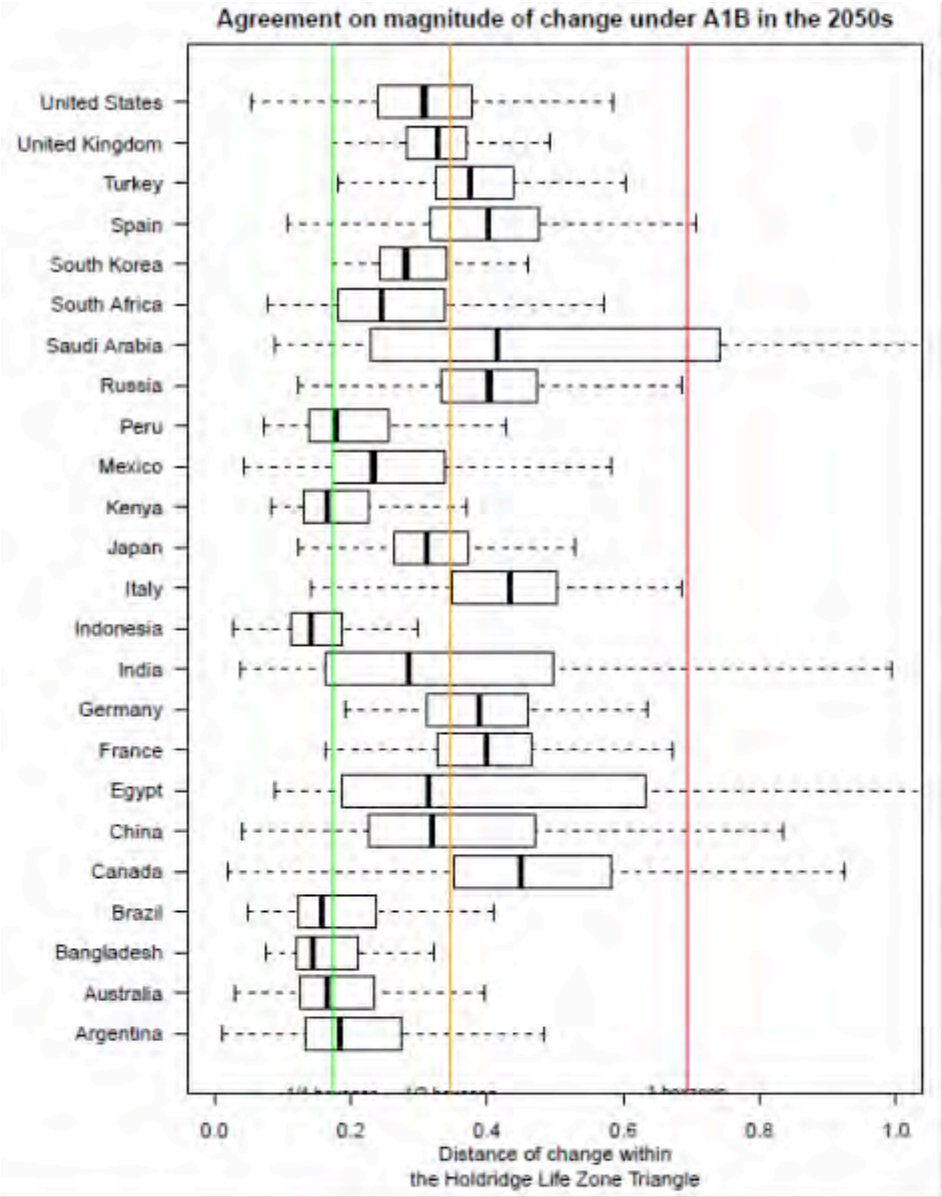
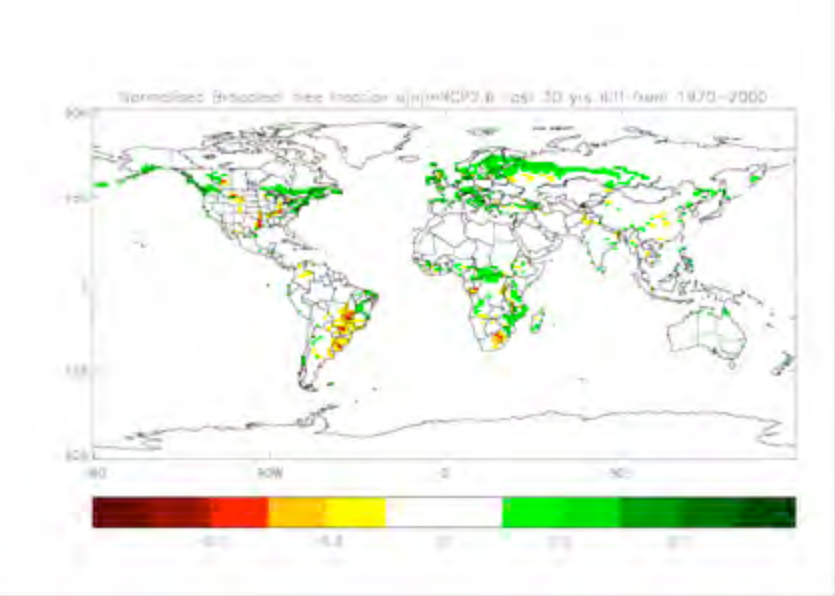
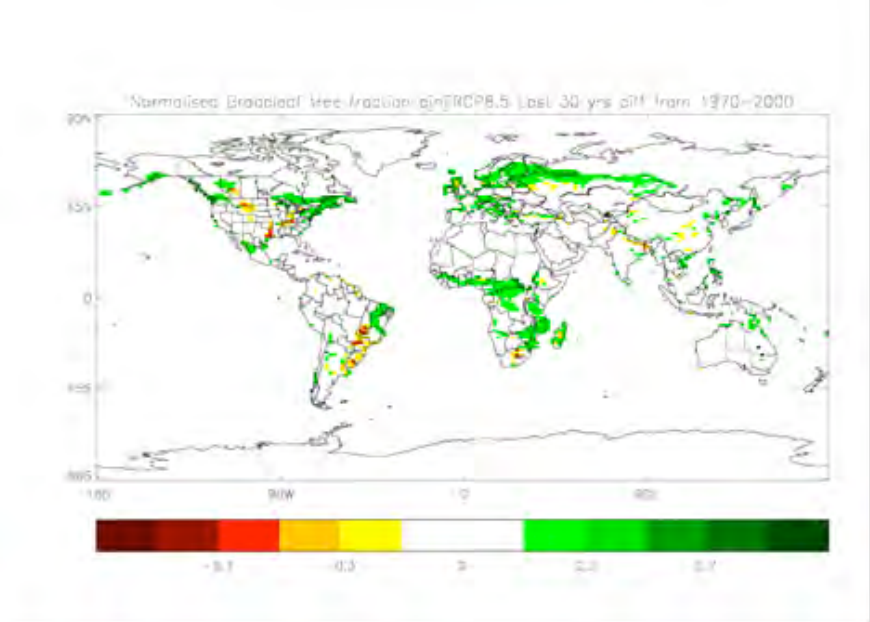


Figure on projected changes in terrestrial ecosystems from ESMs

A key factor here is that at global and continental scales, the projections of direct anthropogenic land cover change generally have a greater impact on PFT coverage than radiatively-forced climate change.





CASE STUDY UNDER CONSIDERATION

Observed forest dieback

Scientists and forest managers are increasingly concerned by the very recent and rapid rise in tree mortality across the globe. A global analysis suggests that tree mortality is rising due to late 20th century and early 21st century climate change in nearly all types of forest across the globe (C. D. Allen, et al., 2010). Several other regional syntheses have drawn the same conclusion. For example, the mortality of many woody species is increasing the Mediterranean region related to dry and warm conditions that prevailed over the last two decades of the 20th century (?Penuelas & Boada, 2003). There is also evidence for increasing tree dieback in many species and in all age classes in Western US (van Mantgem, et al., 2009) and in several temperate tree species in Europe even in the center of their ranges (Breda, Huc, Granier, & Dreyer, 2006). Tree mortality is also increasing in tropical forests, based on measurements from large networks of monitoring sites (Lewis, Lloyd, Sitch, Mitchard, & Laurance, 2009). The most serious, large-scale mortality events are due to climate-related increases in insect attacks (e.g., Kurz et al., 2008). Outside of these events mortality is currently at non-catastrophic levels (van Mantgem, et al., 2009, C. D. Allen, et al., 2010).

Attribution of recent forest dieback to climate change remains a major difficulty because of our weak understanding of the factors mediating tree mortality (C. D. Allen, et al., 2010). However, detailed analyses have clearly identified recent trends in temperature and precipitation as major drivers of tree mortality in specific cases (?Bigler, Braker, Bugmann, Dobbertin, & Rigling, 2006, Breda & Badeau, 2008, Breshears et al., 2009). These trends in tree mortality are backed up experiments (e.g., Ogaya & Penuelas, 2007, D. C. Nepstad, et al., 2007) and by model predictions of tree range shifts due to climate change in which large areas of current species ranges, especially at trailing edges of ranges, have and will become increasingly unsuitable for long-term persistence (refs). It is too early, however, to know if the relatively modest levels of tree mortality currently occurring are harbingers of massive forest dieback to come in the next few decades.

[NOTE: might be worth trying to make a figure for this.]