PAPER
15

CLIMATE CHANGE: ENVIRONMENTAL EFFECTS AND MANAGEMENT ADAPTATIONS

ROBERT C. SZARO[1] and BYRON K. WILLIAMS[1]

[1] Biological Resources Discipline, US Geological Survey

ABSTRACT: Species, natural communities, and ecological systems have evolved over time in response to changing and dynamic environments. The natural variation of the physical environment and biotic interactions within that environment create a dynamic template that shapes how species evolve and what species may (or may not) be able to persist in any given area. Rapidly changing climate has potentially profound implications for nature conservation and threatened and endangered species management. Predictions include dramatic shifts in species populations and their distributions with potentially increased extinction risk for those species with restricted ranges, limited distribution, or mobility. For example, the rate of future climate change will likely exceed the migration rates of most plant species. Given likely future climate scenarios, conservation planners need to develop and use objective-driven learning-based adaptive strategies.

Keywords: global change, climate change, adaptive management strategies, adaptation, adaptive capacity, multiple scales

1. Introduction

The impact of human actions on the rate and direction of global environmental change is already being felt on biodiversity around the globe (Millennium Ecosystem Assessment, 2005). Present evidence suggests strong and persistent effects of such change on both plants and animals as evidenced by substantial changes to the phenology and distribution of many taxa (Parmesan and Yohe, 2003; Root and Schneider, 1995, 2003). For example, the onset of bird nesting, budburst, and migrant arrivals has markedly shifted over the last few decades and many species (for example, birds and butterflies) have extended their ranges further northward (Parmesan *et al.*, 1999; Walther *et al.*, 2002).

Some of the most pronounced ecological responses to climatic warming are expected in polar marine regions, where temperature increases have been the greatest and sea ice serves as a sensitive indicator of changes in climatic conditions and effects on ice dependent species (Regehr *et al.*, 2007). Terrestrial Arctic animals will be vulnerable to warmer and drier summers, climatic changes that interfere with migration routes and staging areas, altered snow and ice conditions and freeze-thaw cycles in winter, climate-induced disruption of the seasonal timing of reproduction and development, and influx of new competitors, predators, parasites and diseases (Callaghan *et al.*, 2004). One of the most striking examples is the concern over declines in Arctic sea ice and its effects on the long-term conservation of polar bears (*Ursus maritimus*). Recent changes in temperature and atmospheric circulation have led to marked declines in the thickness, extent, and duration of sea ice in many parts of the Arctic (Rigor and Wallace, 2004; Belchansky *et al.*, 2005; Stroeve *et al.*, 2005; Holland *et al.*, 2006). At the southern limit of polar bear range, a progressive change toward earlier breakup of sea ice has been shown to negatively influence body condition, reproductive rates and survival of bears (Stirling *et al.*, 1999; Obbard 2006; Regehr 2007b). Most recently, Regehr *et al.* (2007a) and Hunter *et al.* (2007) have shown that both survival rates and total population size of the Southern Beaufort Sea polar bear population appears to be in decline and are also significantly correlated with changes in ice distribution and the duration of the open water season. Projected changes in future sea ice conditions, if realized, will result in the loss of approximately 2/3 of the world's current polar bear population by the mid 21st century. Because models of melting Arctic sea ice are likely to have grossly underestimated the rate of projected melting the current assessment of future polar bear status may be overly optimistic (Amos, 2007; Whelan *et al.*, 2007).

Other areas where climate change influence is pronounced are in various mountain regions where climate-induced vegetation change has been well documented (Walther *et al.*, 2001) and for high-alpine assemblages in particular (Keller *et al.*, 2000; Theurillat and Guisan, 2001; Korner, 2003). Holzinger *et al.* (2008) found an increased number of vascular plant species of as many as three species per decade within the last 120 years on high alpine summits in Switzerland. They noted upward migration rates were within the range of several meters per decade, which is similar to results of in other studies (Grabherr *et al.*, 1994). These changes seem to be connected to temperature increases over the past century (Grabherr *et al.*, 2001; Walther *et al.*, 2005).

The process of adaptation by species or ecosystems to climate occurs in a variety of ways under many circumstances and is not likely to affect all species in the same way (Millennium Ecosystem Assessment, 2005). The process depends on many factors, including who or what adapts, what they adapt to, how they adapt, what resources are used and how, and the effects of adaptation within and across ecosystems, species and genetic levels (MacIver and Wheaton, 2005). Some species or communities will be more prone to extinction than others due to the direct or underlying effects of such climate change, and the risk of extinction will increase particularly for those species that are already on the verge of extinction. Vulnerable species often have limited climatic ranges, restricted habitat requirements, reduced mobility, or isolated or small populations (Millennium Ecosystem Assessment, 2005).

From a conservation perspective, adapting to changing climate poses a daunting task. Oftentimes managers develop plans for specific parts of the landscape using past conditions as a guide to judge future outcomes. But what if future conditions differ greatly from those in the past? Does it make sense to manage for outcomes that are probably impossible to achieve? Does it make sense to manage areas as if they were islands? Can we make decisions requiring an interlocking cascade of actions across broad landscapes? Does it matter if a species exists in a particular location or is it more important to ensure that it exists somewhere? Such questions make adapting to changing climate regimes much more complicated than the conservation approaches used up until now. Conservation becomes a moving target in a climatically changing environment, and although current reserve systems are a starting point, there is no clear end point (Von Maltitz *et al.*, 2006).

2. Climate Influences on Ecosystem Disturbances

Climate change, which contributes to habitat change, is becoming the dominant driver of changes in habitat condition, particularly for vulnerable species and habitats such as endemic montane, island, and peninsula species and coastal habitats such as mangroves, coral reefs, and coastal wetlands (Millennium Ecosystem Assessment, 2005). Both recent empirical evidence and predictive modeling studies suggest that climate change will increase population losses in many areas. Although there may be an increase in some regions in local biodiversity (usually as a result of species introductions), the long-term consequences of these increases are hard to foresee.

A review of how disturbances are influenced by climate and might be exacerbated by climate change provides a background for examining ways to deal with the impacts of climate change upon ecosystems and their services (Dale *et al.*, 2001). The effect of each individual disturbance is partly tempered by prior adaptations to previous disturbances as well as by current conditions, which are a function of past management practices. Assessments and decisions based mainly on global modeling efforts would likely overlook the potentially large ecological, social and economic impact that may occur at regional and local scales (Higgins and Vellinga, 2004). This highlights the importance of scale in assessing ecosystem responses and in scaling global models to regional and local levels. Effects of climate extremes on forests can have both short-term and long-term implications for standing biomass, tree health and species composition (Dale *et al.*, 2001; Bush *et al.*, 2004), and similar effects apply to semi-natural grasslands (Grime *et al.*, 1994). In addition, by creating forest gaps, disturbances can provide places where species better suited to new prevailing climate regimes can become established. Specific disturbances that affect and are affected by climate change are fire, drought, floods, insect and pathogen outbreaks, invasive species, hurricanes, ice storms, landslides, sea level rise and interactions among these disturbances.

FIRE: In 2003, large fires in southeastern Australia, western Canada, Mediterranean Europe, and southern California drew considerable public and political attention to fire as a phenomenon through which ecological and human dynamics collide (Lavorel *et al.*, 2007). The frequency, size, intensity, seasonality, and type of fires depend on interactions among climate, vegetation structure, and land use on local to regional scales (Dale *et al.*, 2001, Lavorel *et al.*, 2007). Fire initiation, propagation and spread depend on the amount and frequency of precipitation, the presence of ignition agents, and conditions (for example, lightning, fuel availability and distribution, topography, temperature, relative humidity, and wind velocity). Fires and their effects on terrestrial ecosystems are highly sensitive to climate change and can have dramatic impacts in the structure and functioning of ecosystems (Lavorel *et al.*, 2007). For example, the projected climatic changes for the next century (IPCC, 2007a) are faster and more profound than any experienced in the last 40,000 years (Bush *et al.*, 2004), and probably in the last 100,000 years. The simplification of ecological structure in Amazonia from complex forest to the simplicity of agriculture coupled with the increased probability of human-set fires and complex ecological interactions mediated by climate takes us into unknown bioclimatic territory (Bush and Lovejoy, 2007). Especially as it is now known that the hydrological cycle (rain coming from moisture from the ocean that is transpired by plants), which produces a significant fraction of Amazon rainfall, is also responsible for 40% of the rain south of the forest in Brazil and northern Argentina. With 20% of the Brazilian Amazon deforested, the point at which an irreversible drying trend is triggered cannot be far away. The immediate consequence of that alteration to the modern hydrological cycle, forest fragmentation, and human activity is the increased probability of Amazonian wildfire (Bush and Lovejoy, 2007).

DROUGHT: Droughts can occur in nearly all ecosystems (Dale *et al.*, 2001). Drought effects are influenced by soil texture and depth; length and severity of exposure; and species present and life stage. Ecosystem responses likely will include feedbacks to the climate system with some potentially significant positive feedbacks occurring in biotic responses to changes in the hydrological cycle (Higgins and Vellinga, 2004). These responses will likely amplify the hydrologic impacts of climate change as regions with decreases (increases) in precipitation shift to vegetation with lower (higher) leaf area and smaller (larger) root systems (Higgins and Vellinga, 2004). These changes are likely to lead to decreased (increased) atmospheric moisture through reduced (increased) transpiration (Higgins and Vellinga, 2004). These types of positive feedbacks from vegetation are implicated in persistence of the drought in the Sahel through a reduction in atmospheric moisture and a resulting shift to a self-sustaining dry equilibrium (Wang and Eltahir, 2000).

FLOODS: Evidence is growing that, as a result of global climate change, severe weather events such as heavy precipitation during winter could become more frequent. The likely result is an increased risk of large-scale flooding and loss of topsoil due to erosion (Fuhrer *et al.*, 2006). Large uncertainty in projections of the hydrological cycle make predictions about the magnitude and location of ecosystem perturbations also uncertain, limiting the potential for impact assessment and adaptation (Higgins and Vellinga, 2004).

INSECT AND PATHOGEN OUTBREAKS: Climate influences the survival and spread of insects and pathogens directly, as well as the susceptibility of their hosts and associated ecosystems (Dale *et al.*, 2001). Changes in temperature and precipitation affect herbivore and pathogen survival, reproduction, dispersal, and distribution. Indirect consequences of disturbance from herbivores and pathogens include elimination of nesting trees for birds and negative effects on mycorrhizal fungi (Gehring *et al.*, 1997; Ayres and Lombardero, 2000). Other indirect effects include the impacts of climate on competitors and natural enemies that regulate the abundance of potential pests and pathogens.

INVASIVE SPECIES: Invasive species can affect ecosystems through herbivory, predation, habitat change, competition, alteration of gene pools via hybridization with natives, fire frequency and severity, and disease (as either pathogens or vectors) (Dale *et al.*, 2001). The effects of invasive species should be considered concurrently with changes in native species distribution and abundance that occur as a consequence of climate change (Hansen *et al.*, 2001). The impact of introduced species on ecosystems is influenced by such climatic factors as temperature, drought, and cloud cover (Ayres, 1993). Invasion biology is not yet adept at forecasting impacts of invasions (Williamson, 1999). The complex interactions among introduced species, native communities, managed ecosystems, and climate change compound this forecasting problem (Simberloff, 2000).

HURRICANES: Historical observations suggest that the active hurricane seasons of 2004 and 2005 may be part of a natural cycle in Earth's climate system related to changes in mean sea-surface temperature (SST) in the North Atlantic Ocean (Poore *et al.*, 2007). Hurricanes are well-documented to disturb ecosystems of the eastern and southern coastlines of the United States, as well as those of the Caribbean islands and the Atlantic coast of Central America (Dale *et al.*, 2001). Ocean temperatures and regional climate events influence the tracks, size, frequency, and intensity of hurricanes (Emanuel, 1987). An average of two hurricanes make land every 3 years in the United States (Hebert *et al.*, 1996). Estimates are that the Florida Everglades have been impacted by 38 storms since 1886 (Doyle and Girod, 1997). Mangrove forests, and the fish and wildlife species dependant on them, rely on the interplay of a variety of physical factors for their existence, including salinity of the water, the amount of oxygen in the soil, soil type, nutrient availability, inundation by tides, and air and water temperature, to name a few (Tomlinson, 1986; Smith, 1992). Because of the complex interactions among these factors, wide-scale damage caused by hurricanes may have unforeseen consequences that cascade throughout the ecosystem (Ward and Smith, 2007). Another example is the catastrophic destruction of the floodplain forests of the Pearl River in Louisiana after Hurricane Katrina will have both short- and long-term consequences with the immediate structural changes having significant impacts on migratory birds (Faulkner *et al.*, 2007). Migratory birds are likely to encounter increasingly altered landscapes along their migration paths in part because of projected changes in habitats caused by such disturbances (Barrow *et al.*, 2007). Continued global warming may accelerate the hydrologic cycle by evaporating more water, transporting that water vapor to higher latitudes, and producing more intense and possibly more frequent storms (Emanuel, 1987; Walsh and Pittock, 1998).

WINDSTORMS: Small-scale wind events are products of mesoscale climatic circumstances and thus may be affected by climate change (Dale *et al.*, 2001). However the type and amount of alteration in windstorm characteristics cannot be predicted because these smaller-scale events are below the resolution of today's climate change models. For example, the more humid, warmer weather patterns predicted for the future in the Arctic are expected to increase the windthrow risk of trees through reduced tree anchorage due to a decrease in soil freezing between late autumn and early spring, that is, during the most windy months of the year. (Peltola *et al.*, 1999). Yet, tornadoes, downbursts, and derechos (a widespread and long lived windstorm that is associated with a band of rapidly moving showers or thunderstorms) are probably the most important agents of abiotic disturbance to eastern deciduous forests (Peterson, 2000).

These disturbances can create very large patches of damage and may trigger advanced regeneration, seed germination, and accelerated seedling growth which can change successional patterns, gap dynamics, and other ecosystem-level processes (Peterson and Pickett, 1995).

ICE STORMS: Ice storms are caused by rain falling through subfreezing air masses close to the ground, which super-cool the raindrops and cause them to freeze on impact (Dale *et al.*, 2001). Ice storms have been increasing in frequency over the last 50 years and may be affected by climate change. The 52-year average annual number of severe ice storms in the United States was 1.3. However, the average for 1949–1976 was 1.1 per year, increasing to 1.6 during the 1977–2000 period (Changnon and Changnon, 2002). These storms can be catastrophic disturbance events with potential impacts on carbon sequestration and ecosystem recovery (McCarthy *et al.*, 2006). Ice storms are important disturbances affecting forests over a surprisingly large portion of the USA extending from east Texas to New England (Irland, 2000). In the areas most affected, icing events are a factor that shapes stand composition, structure, and condition over wide areas. Impacts of individual storms are highly patchy and variable, and depend on the nature of the storm.

LANDSLIDES: Climate is an important forcing factor of landslide activity, especially as it effects precipitation and temperature as inputs into the landslide system (Schmidt and Dehn, 2003). Either increases or decreases in landslide activity can occur depending on the direction of change of precipitation and temperature. For example, increasing winter temperature and reduced snow storage has been shown to decrease landslide activity (Schmidt and Dehn, 2003). Both slow and rapid movements of soil, rock, and associated vegetation are triggered directly by climate factors and by climate-influenced processes (for example, stream-bank erosion) (Dale *et al.*, 2001). Triggering climatic events include snowmelt and intense rainfall. Landslide frequency and extent are also influenced by snow accumulation, distribution, and melt rate. Vegetation influences the likelihood of sliding through the soil stabilizing effects of root systems and the effects of vegetation structure and composition on hydrology. Landslides in forest landscapes can damage aquatic resources and threaten public safety but they are also important natural processes contributing to the maintenance of needed structures in stream courses for fish populations.

SEA-LEVEL RISE: Global average sea level rose at an average rate of 1.8 [1.3 to 2.3] mm per year over 1961 to 2003 (IPCC, 2007b). The rate was faster over 1993 to 2003. As sea level rises as a result of global climate change, storm surge floods will become more frequent and larger areas will become inundated (Barros, 2005). For example, in the Coastal Areas of the Río de la Plata, Argentina, the major impact of climate change regarding coastal flooding will be in the increasing frequency of floods caused by storm surges (Barros, 2005). Impacts of sea-level rise will include increased coastal erosion, higher storm-surge flooding, inhibition of primary production processes, more extensive coastal inundation, changes in surface water quality and groundwater characteristics, increased loss of property and coastal habitats, increased flood risk and potential loss of life, loss of nonmonetary cultural resources and values, impacts on agriculture and aquaculture through decline in soil and water quality, and loss of tourism, recreation, and transportation functions (IPCC, 2001b).

INTERACTIONS AMONG DISTURBANCES: Many disturbances are cascading with each successive disturbance building on previous events (Dale *et al.*, 2001). Warming temperatures across western North America, coupled with increased drought, are expected to exacerbate disturbance regimes, particularly wildfires, insect outbreaks, drought, windstorms, and invasions of exotic species (Bachelet *et al.*, 2007; McKenzie and Allen, 2007). Drought often weakens tree vigor, leading to insect infestations, disease, or fire. Insect infestations and disease promote future fires by increasing fuel loads, and fires promote future infestations by compromising tree defenses. Increased fire intensity or extent could also enhance the potential for landslides. One way invasive species can affect native ecosystems is by changing fuel properties, which in turn can affect fire behavior and alter fire regime characteristics such as frequency, intensity, extent, type, and seasonality of fire (Brooks *et al.*, 2004). Hurricanes generally contribute to increased species richness and diversity in coastal forests (Battaglia and Sharitz, 2005) but after Hurricane Katrina and Rita along the Gulf Coast of the United States the invasion of the Chinese tallow tree (Triadica sebifera) became a particular concern (Faulker *et al.*, 2007). Bigler *et al.* (2005) demonstrated the relative importance and the combined effects of fire and beetle outbreak, vegetation, and topography on fire severity during extreme drought in Rocky Mountain subalpine forests. Many ecologists and resource managers expect ecosystems to change more rapidly from disturbance effects than from the direct effects of a changing climate by itself (McKenzie and Allen, 2007).

3. Adapting To Climate Change

Existing climate data and models have highlighted general changes to global climate (English Nature *et al.*, 2003). However, uncertainties remain about the rate and severity of change at the regional and local level. Global change does not mean the same amount of warming everywhere. Some places may even become cooler. The challenge is less about dealing with projected impacts, than it is about developing strategies to manage the uncertainties created by climate change. A precautionary approach is needed that reduces current risk, accounts for the potential movement of species, and keeps future management options open. Developing techniques that allow species and ecosystem resources to be adequately conserved and managed in the face of climate variability will require addressing many challenges.

Climate change will result in both long-term changes in mean temperature and/or precipitation, as well as increases in the frequency of extreme climatic events (UNDP and GEF, 2008). Adaptation responses that focus on dealing with year-to-year risks (for example, forests fires, hurricanes, floods) may not be adequate for coping with long-term climate change impacts (for example, sea-level rise, earlier snow melts, temperature increase). The temporal dimension of climate change effects is therefore an important consideration in the development of effective adaptation strategies (IPCC, 2001a; Niang-Diop and Bosch, 2005). Developing such a strategy is not a simple one-time activity but instead is an iterative, continuous learning process. To ensure effectiveness, strategy development should incorporate the principles of an adaptive management process, including the dynamic reassessment of objectives, actions, monitoring, and implementation as environmental conditions change (Williams *et al.*, 2007).

As a result, conservation planners, managers, and policy makers need to become better informed about the potential consequences of climate change on the resources with which they work (Price and Root, 2004). Given the anticipated impacts of climate change over the next 50 to 200 years, many species will have to move from their current locations to other areas with suitable climates (Von Maltitz *et al.*, 2006). To facilitate this process and minimize species loss, a multitude of strategies are needed. Key elements of these strategies will include creating an environment permeable to species migrations through realignment of reserves, and incorporating land use outside of reserves in the conservation framework.

Among other things, this will require consideration of the placement of conservation areas on a north-south axis or along altitudinal gradients to enhance movements of habitats and wildlife by providing migration corridors or stepping stones. Any management plan needs to be flexible enough to adjust to ongoing and future change (English Nature *et al.*, 2003). This means going beyond a static management plan and moving towards a dynamic approach that tests assumptions, monitors results and adapts management actions accordingly. Such management should aim to enhance current biodiversity and learn how to accommodate the alterations in species range, distribution and population density being triggered by climate change.

When such measures do not meet conservation objectives, other more active approaches may need to be considered. For example, where species are unable to move on their own, facilitated translocations will need to be considered. As a last resort, it may be necessary to engage in ex-situ conservation for species with no possible future habitats (for example, polar bears and sea ice) (Von Maltitz *et al.*, 2006).

Implementing these concepts calls for much more robust conservation thinking and planning. Plans for specific sites must be viewed in the context of potential change. Should plans continue to be retrospective in nature where decisions are based on the range of historical variability? Or should planners ask questions about what species and ecosystems they should manage based on those which will likely persist at that site in the future? This kind of planning cannot be effective at a single site. Rather, an interlinked strategy among sites placed in a broader landscape will allow managers to manage for particular species and ecosystems somewhere in that landscape. Many species will persist, but not necessarily in the same locations.

In addition, there is a need to consider how people will adapt to climate changes and how their changing behavior will affect ecological systems. For example, as the temperatures in Florida increase and severe hurricanes become more prevalent, many Floridians are moving to the eastern Tennessee and western North Carolina. This migration may become more prevalent with sea level rise. The resulting development pressures are occurring in the forested areas of high biodiversity. At the same time, climate changes are resulting in an alteration in the places, seasons, and ways that people recreate that can add new pressures to ecological systems (Hall and Higham, 2005; Richardson and Loomis, 2004). Comprehensive strategies to cope with climate change will need to consider both natural and socio-political impacts.

Finally, changes will be needed not only in management concepts but also in legal constraints and opportunities. In particular, managing for threatened and endangered species will be problematic. The concepts of critical habitat and viable species populations are often tied to particular places or areas. But what if habitat for a threatened or endangered species migrates further upslope or northward as climate conditions change? Should a manager be held accountable for declines in habitats or species that can no longer exist in that particular place or area because of changes in the environment (warmer or cooler; wetter or drier) and not as a result of management action? Conservation has always been challenging, but now it is even more so in this era of dynamic climate change and conservation.

A learning-based approach to decision making seems especially well suited for meeting these challenges (Williams *et al.*, 2007). A prominent example is adaptive management, which applies to resource systems that are dynamic and influenced by evolving environmental conditions and management strategies. In particular, adaptive management is applicable to systems that are subject to uncertainties about environmental and management impacts which limit effective adaptation. From the above, it is clear that temporal variation and uncertainty are key attributes of ecosystems that must be managed in the face of climate change. An adaptive approach to climate change recognizes uncertainty, and the need to learn about climate impacts and adaptation through time. It must involve stakeholders in scoping and scaling adaptation strategy, as well as the monitoring and assessment of impacts. Finally, it builds directly on learning, to produce improved adaptive strategy based on what is learned. It is through such an objective driven, science-based approach that opportunities for adaptation can best be recognized and implemented, and threats from climate change can be ameliorated.

References

Amos, J. 2007. Arctic summers ice-free ‘by 2013’. BBC News 12 December 2007. Available online at: **http://news.bbc.co.uk/2/hi/science/nature/7139797.stm**.

Angeler, D.G. 2007. Resurrection ecology and global climate change research in freshwater ecosystems. *Journal of the North American Benthological Society* 26(1):12–22.

Ayres, M.P. 1993. Global change, plant defense, and herbivory. Pages 75–94 in Kareiva P.K., J.G. Kingsolver, and R.B. Huey, eds. *Biotic Interactions and Global Change.* Sunderland (MA): Sinauer Associates.

Ayres, M.P., and M.J. Lombardero.2000. Assessing the consequences of climate change for forest herbivore and pathogens. *The Science of the Total Environment* 262:263-286.

Bachelet, D., J.M. Lenihan and R.P. Neilson. 2007. Wildfires and Global climate change: The Importance of Climate Change for Future Wildfire Scenarios in the Western United States. Pew Center on Global Climate Change, Arlington, VA.

Barros, V. 2005. Global Climate Change and the Coastal Areas of the Río de la Plata. A Final Report Submitted to Assessments of Impacts and Adaptations to Climate Change (AIACC), Project No. LA 26. 124pp.

Barrow, W. Jr., J. Buler, B. Couvillion, R. Diehl, S. Faulkner, F. Moore, and L. Randall. 2007. Broad-scale Response of Landbird Migration to the Immediate Effects of Hurricane Katrina. Pages 131-136 in Farris, G.S., Smith, G.J., Crane, M.P., Demas, C.R., Robbins, L.L., and Lavoie, D.L. (eds.). Science and the storms-the USGS response to the hurricanes of 2005: U.S. *Geological Survey Circular* 1306, 283p.

Battaglia, L. L. and R. R. Sharitz. 2005. Effects of natural disturbance on bottomland hardwood regeneration. p. 121-136. In Ecology and Management of Bottomland Hardwood Systems: The State of Our Understanding, edited by L.H. Fredrickson, S.L. King, and R.M. Kaminski. University of Missouri-Columbia, Gaylord Memorial Laboratory Special Publication No. 10.

Belchansky, G.I., D.C. Douglas, and N.G. Platonov. 2005. Spatial and temporal variations in the age structure of Arctic sea ice. *Geophysical Research Letters* 32:L18504.

Berteaux, D., D. Réale, A.G. McAdam, and S. Boutin. 2004. Keeping Pace with Fast Climate Change: Can Arctic Life Count on Evolution? *Integrative and comparative Biology* 44(2):140–151.

Bigler, C., D. Kulakowski, and T. T. Veblen. 2005. Multiple disturbance interactions and drought influence fire severity in rocky mountain subalpine forests. *Ecology* 86:3018-3029.

Boonstra, R. 2004. *Coping with Changing Northern Environments: The Role of the Stress Axis in Birds and Mammals Integrative and Comparative Biology* 44(2):95–108.

Bradshaw, W.E., P.A. Zani, and C.M. Holzapfel. 2004. Adaptation to Temperate Climates. *Evolution* 58(8):1748–1762.

Brooks, M.L., C.M. D'antonio, D.M. Richardson, J.B. Grace, J.E. Keeley, J.M. Ditomaso, R.J. Hobbs, M. Pellant, and D. Pyke. 2004. Effects of Invasive Alien Plants on Fire Regimes. *BioScience* 54(7):677-688.

Bush, M.B. and T.E. Lovejoy. 2007. Amazonian conservation: pushing the limits of biogeographical knowledge. *Journal of Biogeography* 34:1291–1293.

Bush, M.B., M.R. Silman and D.H. Urrego. 2004. 48,000 years of climate and forest change in a biodiversity hot spot. *Science* 303:827–829.

Callaghan, T.V., L.O. Björn, Y. Chernov, T. Chapin,T.R. Christensen, B. Huntley, R.A. Ims, M. Johansson, D. Jolly, S. Jonasson, N. Matveyeva, N. Panikov, W. Oechel, G. Shaver, J. Elster, H. Henttonen, K. Laine, K. Taulavuori, E. Taulavuori, and C. Zöckler. 2004. Biodiversity, Distributions and Adaptations of Arctic Species in the Context of Environmental Change. *Ambio* 33(7):404–417.

Changnon S.A. and J.M. Changnon. 2002. Major ice storms in the United States, 1949-2000. *Global Environmental Change Part B: Environmental Hazards* 4(4):105-111.

Chapin III, F.S., M. Hoel, S.R. Carpenter, J. Lubchenco, B. Walker, T.V. Callaghan, C. Folke, S.A. Levin, K.G. Mäler, C. Nilsson, S. Barrett, F. Berkes, A.S. Crépin, K. Danell, T. Rosswall, D. Starrett, A. Xepapadeas, and S.A. Zimov. 2006. Building Resilience and Adaptation to Manage Arctic Change. *Ambio* 35(4):198–202.

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Peterson, D. Simberloff, F.J. Swanson, B.J. Stocks, and B.M. Wotton. 2001. Climate Change and Forest Disturbances. *BioScience* 51(9):723-734.

DeWeaver, E. 2007. Uncertainty in Climate Model Projections of Arctic Sea Ice Decline: An Evaluation Relevant to Polar Bears. USGS Alaska Science Center, Anchorage, *Administrative Report.* 40pp.

Doyle, T. W., and G. Girod. 1997. The frequency and intensity of Atlantic hurricanes and their influence on the structure of south Florida mangrove communities. In H. Diaz and R. Pulwarty, (Ed.). Hurricanes, climatic change and socioeconomic impacts: a current perspective. Westview Press, New York, N.Y. pp. 111-128.

Emanuel, K.A. 1987. The dependence of hurricane frequency on climate. *Nature* 326: 483-485.

English Nature, IUCN-The World Conservation, Union, the Royal Society for the Protection of Birds, the World Conservation Monitoring Centre of the United Nations Environment Programme, and the World Wide Fund for Nature. 2003. *Climate Change and Nature: Adapting for the Future.* Available online at: http://www.iucn.org/themes/climate/wl/documents/cc&nature_adapting_for_future.pdf.

Faulkner, S., W. Barrow, B. Couvillion, W. Conner, L. Randall, and M. Baldwin. 2007. Impacts of Hurricane Katrina on Floodplain Forests of the Pearl River. Pages 125-130 in Farris, G.S., Smith, G.J., Crane, M.P., Demas, C.R., Robbins, L.L., and Lavoie, D.L. (eds.). Science and the storms-the USGS response to the hurricanes of 2005: U.S. Geological Survey Circular 1306, 283p.

Fuhrer, J., M. Beniston, A. Fischlin, Ch. Frei, S. Goyette2 K. Jasper and Ch. Pfister. 2006. Climate Risks and Their Impact on Agriculture and Forests in Switzerland. *Climatic Change* 79(1-2):79–102.

Grabherr G., M. and P.H. Gottfried. 1994. Climate effects on mountain plants. *Nature* 369:448.

Grabherr G., M. Gottfried and H. Pauli. 2001. Aspects of global change in the Alps and in the high arctic region. Long-term monitoring of mountain peaks in the Alps. In: Burga CA, Kratochwil A (eds) Biomonitoring: General and applied aspects on regional and global scales. Kluwer Academic Publishers, Dordrecht, pp 153–177.

Grime JP, Willis AJ, Hunt R, Dunnett NP (1994) Climate-vegetation relationships in the Bibury road verge experiments. In: Leigh RA, Johnston AE (eds) Long-term experiments in agricultural and ecological sciences. CAB International, Wallingford, UK, pp 271–285.

Groffman, P.M., J.S. Baron, T. Blett, A. J. Gold, I. Goodman, L.H. Gunderson, B.M. Levinson, M.A. Palmer, H.W. Paerl, G.D. Peterson, N. L. Poff, D.W. Rejeski, J.F. Reynolds, M.G. Turner, K.C. Weathers and J. Wiens. 2006. Ecological Thresholds: The Key to Successful Environmental Management or an Important Concept with No Practical Application? *Ecosystems* 9(1):1-13.

Hall, C. M., and J. Higham. 2005.Tourism, Recreation and Climate Change. Channel View Publications. Clevedon, UK. 309pp.

Hansen, A.J., R.P. Neilson, V.H. Dale, C.H. Flather, L.R. Iverson, D.J. Currie, S. Shafer, R. Cook, and P.J. Bartlein. 2001. Global change in forests: Responses of species, communities, and biomes. *BioScience* 51: 765-779.

Hebert, P.J., J.D. Jarrell,, and M. Mayfield. 1996. Deadliest, costliest, and most intense United States hurricanes of this century (and other frequently requested hurricane facts). Miami (FL): National Oceanic and Atmospheric Administration, Tropical Prediction Center. NOAA Technical Memorandum MWS-TPC-1.

Higgins, P.A.T. and M. Vellinga. 2004. Ecosystem Responses to Abrupt Climate Change: Teleconnections, Scale and the Hydrological Cycle. Climatic Change 64(1-2): 127-142.

Holl, K.D., E.E. Crone, and C.B. Schultz. 2003. Landscape Restoration: Moving from Generalities to Methodologies. *BioScience* 53(5):491–502.

Holzinger, B., K. Hülber, M. Camenisch and G. Grabherr. 2008. Changes in plant species richness over the last century in the eastern Swiss Alps: elevational gradient, bedrock effects and migration rates. *Plant Ecology* 195: 179-196.

Hopkins, J.J., H.M. Allison, C.A. Walmsley, M. Gaywood and G. Thurgate. 2007. Conserving biodiversity in a changing climate: guidance on building capacity to adapt. Published by Defra on behalf of the UK Biodiversity Partnership. Available online at: **http://www.ukbap.org.uk/Library/BRIG/CBCCGuidance.pdf**.

Holland, M.M., C.M. Bitz, E.C. Hunke, W.H. Lipscomb, and J.L. Schramm. 2006. Influence of the sea ice thickness distribution on polar climate in CCSM3. *Journal of Climate* 19(11):2398-2414.

Huey, R.B., M. Carlson, L. Crozier, M. Frazier, H. Hamilton, C. Harley, A. Hoang, and J.G. Kingsolver. 2002. Plants Versus Animals: Do They Deal with Stress in Different Ways? *Integrative and Comparative Biology* 42(3):415–423.

Hunter, C.M., H. Caswell, M.C. Runge, E.V. Regehr, S.C. Amstrup, and I. Stirling. 2007. Polar Bears in the Southern Beaufort Sea II: Demography and Population Growth in Relation to Sea Ice Conditions. USGS Alaska Science Center, Anchorage, Administrative Report. 46pp.

IUCN-The World Conservation Union. 2001.Climate Change and Species Survival: Implications for Conservation Strategies, Discussion paper presented at the IUCN Workshop on Climate Change and Species Survival in January 2001, Gland, Switzerland. Implications of Climate Change for Species Conservation. **http://www.iucn.org/themes/climate/docs/ccspeciessurvival.pdf**.

IPCC. 2001a. *IPCC Third Assessment Report: Climate Change 2001.* Intergovernmental Panel on Climate Change, Geneva. Available online at: **http://www.ipcc.ch/ipccreports/assessments-reports.htm**.

IPCC. 2001b. *Climate Change 2001: Working Group II: Impacts, Adaptation and Vulnerability.* Available online at: **http://www.grida.no/climate/ipcc_tar/wg2/292.htm**.

IPCC. 2007a. *Climate Change 2007: climate change impacts, adaptation and vulnerability.* Intergovernmental Panel on Climate Change, Geneva.

IPCC. 2007b Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Irland, L.C. 2000. Ice storms and forest impacts. *The Science of the Total Environment* 262(3):231-242.

Johnston, M., T. Williamson, D. Price, D. Spittlehouse, A. Wellstead, P. Gray, D. Scott, S. Askew, and S. Webber. 2006. Adapting Forest Management to the Impacts of Climate Change in Canada. BIOCAP Canada. Available online at: **http://www.biocap.ca/rif/report/Johnston_M.pdf**.

Jones, R.N., P. Dettmann, G. Park, M. Rogers and T. White. 2007. The relationship between adaptation and mitigation in managing climate change risks: a regional response from North Central Victoria, Australia. Mitigation and Adaptation Strategies for Global Change 12:685-712.

Keller, F., F. Kienast, and M. Beniston. 2000. Evidence of response of vegetation to climatic change on high elevation sites in the Swiss Alps. *Regional Environmental Change* 2:70-77.

King D.A. 2004. Climate Change Science: Adapt, Mitigate, or Ignore?", *Science,* 303: 176-177.

Korner, C. 2003. Alpine plant life. Functional plant ecology of high mountain cosystems. Springer, Berlin.

Kozlowski, T.T. and S.G. Pallardy. 2002. Acclimation and Adaptive Responses of Woody Plants to Environmental Stresses. *The Botanical Review* 68(2):270–334.

Lavorel, S., M.D. Flannigan, E.F. Lambin and M.C. Scholes. 2007. Vulnerability of land systems to fire: Interactions among humans, climate, the atmosphere, and ecosystems. *Mitigation and Adaptation Strategies for Global Change* 12(1): 33-53.

Lim, B. E. Spanger-Siegfried, I. Burton, E. Malone and S. Huq. 2005. Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures. Cambridge University Press, Cambridge. McCarthy, H. R., R. Oren, H.-S. Kim, K. H. Johnsen, C. Maier, S. G. Pritchard, and M. A. Davis. 2006., Interaction of ice storms and management practices on current carbon sequestration in forests with potential mitigation under future CO_2 atmosphere, *Journal of Geophysical Research* 111, D15103.

MacIver, D.C. and E. Wheaton. 2005. Tomorrow's Forests: Adapting to A Changing Climate. *Climatic Change* 70(1-2):273-282.

McKenney, D.W., J.H. Pedlar, K. Lawrence, K. Campbell, and M.F. Hutchinson. 2007. Potential Impacts of Climate Change on the Distribution of North American Trees. *BioScience* 57(11):939–948.

McKenzie, D. and C.D. Allen. 2007. EOS, *Transactions American Geophysical Union* 88(21):227.

Millennium Ecosystem Assessment. 2005a. Ecosystems and Human Well-Being: Current State and Trends, Volume 1. Island Press, Washington. 948p.

Millennium Ecosystem Assessment, 2005b. Ecosystems and Human Well-being: Biodiversity Synthesis. World Resources Institute, Washington, DC.

Niang-Diop, I. and H. Bosch. 2005. Formulating an Adaptation Strategy. Pages 185-204 in Lim, B. E. Spanger-Siegfried, I. Burton, E. Malone and S. Huq, Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures. Cambridge University Press, Cambridge.

Obbard, M.E., Cattet, M.R.L., Moddy, T., Walton, L.R., Potter, D., Inglis, J., and C. Chenier. 2006. Temporal trends in the body condition of southern Hudson Bay polar bears. Climate Change Research Information Note 3:1-8. Available from **http://sit.mnr.gov.on.ca**.

Obbard, M.E., T.L. McDonald, E.J. Howe, E.V. Regehr, and E.S. Richardson. 2007. Polar Bear Population Status in Southern Hudson Bay, Canada. USGS Alaska Science Center, Anchorage, Administrative Report. 36pp.

Peltola, H., S. Kellomäki and H. Väisänen. 1999. Model Computations of the Impact of Climatic Change on the Windthrow Risk of Trees. *Climatic Change* 41(1):17-36.

Poore, R.Z., T. Quinn, J. Richey, and J.L. Smith. 2007. Cycles of Hurricane Landfalls on the Eastern United States Linked to Changes in Atlantic Sea-surface Temperatures. Pages 7-11 136 in Farris, G.S., Smith, G.J., Crane, M.P., Demas, C.R., Robbins, L.L., and Lavoie, D.L. (eds.). Science and the storms-the USGS response to the hurricanes of 2005: U.S. Geological Survey Circular 1306, 283p.

Parmesan, C., N. Ryrholm, C.Stefanescu, J.K. Hill, C.D. Thomas, H. Descimon, B. Huntley, L. Kaila, J. Kullberg, T. Tammaru, W. J. Tennent, J.A. Thomas and M. Warren. 1999. Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* 399:579-583.

Parmesan, C. and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421:37-42.

Peterson, C.J. 2000. Catastrophic wind damage to North American forests and the potential impact of climate change. Science of the Total Environment 262: 287-311.

Peterson, C.J. and S.T.A. Pickett. 1995. Forest reorganization: A case study in an old growth forest catastrophic blowdown. *Ecology* 76: 763-774.

Price, J.T. and T.L. Root. 2004. Ecosystem Functioning Under Abrupt Climate Change, Potential Surprises and Adaptations. Draft Paper presented at Abrupt Climate Change (ACC) Strategy Paris Workshop. Available online at: **http://www.accstrategy.org/draftpapers/ACCSpriceroot.pdf**.

Regehr, E.V., S.C. Amstrup, and I. Stirling. 2006. Polar Bear Population Status in the Southern Beaufort Sea. USGS Alaska Science Center, Anchorage, Open File Report 1337.

Regehr, E.V., C.M. Hunter, H. Caswell, S.C. Amstrup, and I. Stirling. 2007a. Polar Bears in the Southern Beaufort Sea I: Survival and Breeding in Relation to Sea Ice Conditions, 2001-2006. USGS Alaska Science Center, Anchorage, Administrative Report. 45pp.

Regehr, E.V., N.J. Lunn, S.C. Amstrup, and I. Stirling. 2007b. Survival and population size of polar bears in western Hudson Bay in relation to earlier sea ice breakup. *Journal of Wildlife Management* 71(8): 2673–2683.

Richardson, R.B. and J.B. Loomis. 2004. Adaptive recreation planning and climate change: a contingent visitation approach, *Ecological Economics* 50(1-2):83-99.

Rigor, I.G., and J.M. Wallace. 2004. Variations in age of Arctic sea ice and summer sea-ice extent. *Geophysical Research Letters* 31:L09401.

Rode, K.D., S.C. Amstrup, and E.V. Regehr. 2007. Polar Bears in the Southern Beaufort Sea III: Stature, Mass, and Cub Recruitment in Relationship to Time and Sea Ice Extent Between 1982 and 2006. USGS Alaska Science Center, Anchorage, Administrative Report. 28pp.

Root, T.L. and S.H. Schneider. 1995. Ecology and Climate: Research Strategies and Implications, Science, 269: 334-341.

Root, T.L. and S.H. Schneider. 2003. Strategic Cyclical Scaling: Bridging Five Orders of Magnitude Scale Gaps in Climatic and Ecological Studies, in Rotmans J. and D.S. Rothman (eds.), Scaling Issues in Integrated Assessment, Lisse, The Netherlands: Swets and Zeitlinger Publishers, 179-204.

Schmidt, M. and M. Dehn. 2003. Examining Links Between Climate Change and Landslide Activity Using GCMs: Case studies from Italy and New Zealand. Advances in Global Change Research, Linking Climate Change to Land Surface Change 6: 123-141.

Schneider, S.H. 2003. Abrupt Non-Linear Climate Change, Irreversibility and Surprise, OECD Workshop on the Benefits of Climate Policy: Improving Information for Policy Makers, Working Party on Global and Structural Policies, 32 pp. Available online at: **http://www.oecd.org/dataoecd/9/59/2482280.pdf**.

Schneider, S.H., W.E. Easterling, and L. Mearns. 2000. Adaptation: Sensitivity to Natural Variability, Agent Assumptions and Dynamic Climate Changes. *Climatic Change,* 45(1): 203-221.

Simberloff, D. 2000. Nonindigenous species: a global threat to biodiversity and stability. Pages 325-334 in P. H. Raven, editor. Nature and human society : the quest for a sustainable world. National Academy Press, Washington, D.C., USA.

Smith, T.J. 1992. Forest structure. In A.I. Robertson and D.M. Alongi (Eds.), Tropical Mangrove Ecosystems. Coastal and Estuarine Studies No. 41, American Geophysical Union, Washington D.C. pp. 101-136.

Stirling, I, T.L. McDonald, E.S. Richardson, and E.V. Regehr. 2007. Polar Bear Population Status in the Northern Beaufort Sea. USGS Alaska Science Center, Anchorage, Administrative Report. 33pp.

Stirling I., Lunn N. J., Iacozza J. 1999. Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climatic change. Arctic. 52: 294–306.

Stroeve, J.C., M.C. Serreze, F. Fetterer, T. Arbetter, W. Meier, J. Maslanik, and K. Knowles. 2005. Tracking the Arctic's shrinking ice cover: Another extreme September minimum in 2004. *Geophysical Research Letters.* 32:L04501.

Theurillat, J-P., and A. Guisan. 2001. Potential impact of climate change on vegetation in the European Alps: a review Clim. Change, 50:77–109.

Tomlinson, P.B. 1986, The botany of mangroves: Cambridge, UK, Cambridge University Press, p. 413.

Von Maltitz, G.P., R.J. Scholes, B. Erasmus and A. Letsoalo. 2006. Adapting conservation Strategies to Accommodate Impacts of Climate Change in Southern Africa. AIACC Working Paper No. 35: Available online at: **http://www.aiaccproject.org/working_papers/Working%20Papers/AIACC_WP35_vonMaltitz.pdf**.

Walsh K., and A.B. Pittock. 1998. Potential changes in tropical storms, hurricanes, and extreme rainfall events as a result of climate change. *Climatic Change* 39: 199-213.

Walther G.R., S. Beissner and C.A. Burga. 2005. Trends in the upward shift of alpine plants. *J. Veg. Sci* 16:541–548.

Walther G.R., C.A. Burga, and P.J. Edwards (eds). 2001. Fingerprints of climate change-adapted behaviour and shifting species ranges. Kluwer Academic Publishers, New York.

Wang, G. L. and Eltahir, E. A. B. 2000. Role of Vegetation Dynamics in Enhancing the Low-Frequency Variability of the Sahel Rainfall. *Water Resour. Res.* 36:1013–1021.

Ward, G.A., and T.J. Smith, III. 2007. Predicting Mangrove Forest Recovery on the Southwest Coast of Florida Following the Impact of Hurricane Wilma, October 2005. Pages 175-182 in Farris, G.S., Smith, G.J., Crane, M.P., Demas, C.R., Robbins, L.L., and Lavoie, D.L. (eds.). Science and the storms-the USGS response to the hurricanes of 2005: U.S. Geological Survey Circular 1306, 283p.

Whelan, J, Maslowski, W, Clement Kinney, J L., and Jakacki, J. 2007. Understanding Recent Variability in the Arctic Sea Ice Thickness and Volume - Synthesis of Model Results and Observations. Eos Trans. AGU, 88(52), Fall Meet. Suppl., Abstract C22A-06.

Williams, J.E. 2000. The Biodiversity Crisis and Adaptation to Climate Change: A Case Study from Australia's Forests. Environmental Monitoring and Assessment 61(1):65-74.

Williams, B.K., R.C. Szaro, and C.D. Shapiro. 2007. Adaptive Management: The U.S. Department of the Interior Technical Guide. Adaptive Management Working Group, U.S. Department of the Interior, Washington, DC.

Williamson M. 1999. Invasions. *Ecography* 22: 5-12.

UNDP and GEF (United Nations Development Programme and Global Environment Facility). 2008. Programming Climate Change Adaptation: Adaptation Measures. Available online at: **http://www.undp.org/gef/adaptation/climate_change/02d.htm**.