5. Biodiversity

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5.1 Introduction and Framework

The potential impacts of climate change on biological diversity at all levels of biological and ecological organization have been of concern to the scientific community for some time (Lovejoy and Peterson 198x, IPCC 1990). However, in recent years, the scientific literature has additionally focused on a variety of observed changes in biodiversity, as well as continuing to explore the potential for changes due to changes in the physical climate system (IPCC 2002 2007; Millennium Ecosystem Assessment 2005). In this chapter, we summarize and evaluate the current knowledge-base on both observed and potential impacts with respect to the following topics:

- Changes in Species Distributions and Phenologies
- Changes in Community Composition
- Changes in Rare or Sensitive Ecosystems

In doing so, our focus is mainly, although not exclusively, on ecosystems within the United States. We also begin to explore the implications of changes in biological diversity for the provisions of ecosystem services (Millennium Ecosystem Assessment 2005), and finally, explore the implications of these findings for observation and monitoring systems.

5.2 Changes in Distribution and Phenologies in Terrestrial Ecosystems

5.2.1 Introduction

Terrestrial systems are already being demonstrably impacted by climate change. There are observable impacts of climate change on terrestrial ecosystems in North America, including changes in the timing of growing season length, phenology, primary production, and species distributions and diversity (Walther 2002; Parmesan 2003). Using modeled climatic variables and observed species data, Root (2005) contends that human activities have contributed significantly to temperature changes, and that human-changed temperatures are associated with discernible changes in plant and animal traits.

Evidence from two meta-analyses (143 studies, Root 2003; 1700 species, Parmesan 2003) and a synthesis (866 studies, Parmesan 2006) on species from a broad array of taxa suggest that there is a significant impact from recent climatic warming in the form of long-term, large-scale alteration of animal and plant populations (Root 2006, 2003; Parmesan 2003). If clear climatic and ecological signals are detectable above the background of climatic and ecological noise from a 0.6°C increase in global mean temperature, by 2050 the impacts on ecosystems will be dramatic (Root 2006).

5.2.2 Growing season length and net primary production

There is evidence indicating a significant lengthening of the growing season and higher net primary productivity (NPP) in the higher latitudes of North America where temperature increases are relatively high. Over the last 19 years, global satellite data indicates an earlier onset of spring across the temperate latitudes by 10-14 days (Myeni 2001; Lucht 2002 #7767), an increase in summer photosynthetic activity (NDVI satellite estimates, Myeni 2001)) and an increase in the amplitude of annual CO_2 cycle (Keeling, 1996), all supported by climatological and field observations. In the higher latitudes in Europe, researchers detected a lengthening of the growing season of 1.1 to 4.9 day per decade since 1951, based on an analysis of climate variables (Menzel 2003). Numerous field studies have documented consistent earlier leaf expansion (Wolfe 2005; Beaubien 2000) and earlier flowering (Schwartz 2000; Cayan 2001) across different species and ecosystem types. Accordingly, NPP in the continental U.S. increased nearly 10 percent between 1982-1998 (Boisvenue 2006). The largest increases in productivity have been documented in croplands and grasslands of the central U.S., as a consequence of favorable changes in water balance (Lobell 2002; Nemani 2002; Hicke 2004). Forest productivity, in contrast, generally limited by low temperature and short growing seasons in the higher latitudes and elevations, has been slowly increasing at less than one percent per decade (Boisvenue 2006; Joos 2002; McKenzie 2001; Caspersen 2000). The exception to this pattern is in forested regions that are subject to drought from climate warming, where growth rates have decreased since 1895 (McKenzie 2001). Recently, widespread mortality over 12,000 km^2 of lower elevational forest in the Southwest demonstrates the impacts of increased temperature and the associated multiyear drought (Breshears 2005) even though previous studies had found productivity at treeline had increased (Swetnam 1998). Disturbances created from the interaction of drought, pests, diseases, and fire are projected to have increasing impacts on forests and their future distributions (IPPC FER SPM 2007). These changes in forests and other ecosystems will cascade through trophic impacting other species.

5.3 Biogeographical and phenological shifts

Movement of species in regions of North America in response to climate warming is expected to result in shifts of species ranges poleward, and upward along elevational gradients (Parmesan 2006). Species differ greatly in their life-history strategies, physiological tolerances, and dispersal abilities, which underlie the high variability in

detecting species responses to climate change. Many animals have evolved powerful mechanisms to regulate their physiology, thereby avoiding some of the direct influences of climate change and instead interact with climate change through indirect pathways involving their food source, habitat, and predators (Schneider 1996). Consequently, most distributional studies tend to focus on animals while phenological studies focus on plants. Although most studies tend to separate distributional and phenological effects of climate change, it is important to keep in mind that the two are not independent and interact with other changing variables to determine species impacts (Parmesan 2006). In addition, most of the observed species responses have described changes in species phenologies (Parmesan 2006). This section will cover both by major taxa type.

Parmesan (2006) describes three types of studies documenting shifts in species ranges: (1) those that measure the an entire species range, (2) those that infer large-scale range shifts from observations across small sections of the species' range, and (3) those that infer large-scale range shifts from small-scale change in species abundances within a local community. Although very few studies have been conducted at a scale the encompasses an entire species' range (amphibians, (Pounds, 1999, 2006), pikas, (Beever 2003) birds, (Dunn, 1999), and butterflies (Parmesan 2006, 1996), there is a growing body of evidence that have inferred large shifts in species range across a very broad array of taxa. In an analysis of 866 peer-reviewed papers exploring the ecological consequences of climate change, nearly 60 percent of the 1598 species studied exhibited shifts in their distributions and/or phenologies over the 20- and 140-year timeframe (Parmesan 2003). Field-based analyses of phenological responses of a wide variety of different species have reported shifts as great as 5.1 days per decade (Root 2003) with an average of 2.3 days per decade across all species (Parmesan 2003).

5.3.1 Migratory birds

For migratory birds, the timing of arrival on breeding territories and over-wintering grounds is an important determinant of reproductive success, survivorship, and fitness. Climate variability and on interannual and longer time scales change can alter phenology and range of migratory birds by influencing the time of arrival and/or the time of departure. The earlier onset of spring has consequences for the timing of migration and breeding in birds which evolved to match peak food availability (Visser 2006). We should expect that the timing of migration would track temporal shifts in food availability caused by changes in climate and the advancement of spring.

The phenology of migration to summer and wintering areas may be disrupted for long-distance, continental migrations as well regional local or elevational migrations. Since short-distance migrants respond to changes in meteorological cues whereas long-distance migrants rely on photoperiod, it has been assumed that the climate signature on changes in phenological cycles would be stronger in short distance than long distance migrants (Lehikoinen 2004). If true, this would lead to greater disruption in the timing of migration relative to food availability for long distance, continental migrants relative to short distance migrants. Recent studies of long-distance migration provide evidence to the

contrary. In continental-scale study of bird phenology that covered the entire United States and Canadian breeding range of a tree swallow (*Tachycineta biocolor*) from 1959 to 1991, Dunn and Winkler documented a 9-day advancement of laying date which correlated with the changes in May temperatures (Winkler 2002; Dunn, 1999). In a study of the first arrival dates of 103 migrant bird species (long-distant, and very long-distant migrants) in the Northeast during the period 1951-1993 compared to 1903-1950, all migrating species arrived significantly earlier, but the birds wintering in the southern U.S. arrived on average 13 days earlier while birds wintering in South America arrived four days earlier (Butler 2003). Conversely, in a reversal of arrival order for short- and long-distance passerines, Jonzen (2006) showed that long-distance migrants have advanced their spring arrival into Scandinavia more than short-distance migrants, based on data from 1980 to 2004. Similarly, in a 42-year analysis of 65 species of migratory birds through Western Europe, researchers found autumn migration of birds wintering south of the Sahara had advanced while migrants wintering north of the Sahara delayed autumn migration (Jenni 2003).

As these studies suggest, when spring migration phenology changes, migrants may be showing a direct response to trends in weather or climatic patterns on the wintering ground and/or along the migration route or there may be indirect microevolutionary responses to the selection pressures for earlier breeding (Jonzen 2006). A climate change signature is apparent in the advancement of spring migration phenology (Root 2003) but the indirect effects may be more important than the direct effects of climate in determining the impact on species persistence and diversity. Indeed, there is no *a priori* reason to expect migrants and their respective food sources to shift their phenologies at the same rate. A differential shift will lead to mistimed reproduction in many species, including seasonally breeding birds. There may be significant consequences of such mistiming if bird populations are unable to adapt (Visser 2004). Phenological shifts in migration timing in response to climate change may lead to the failure of migratory birds to breed at the time of abundant food supply (Visser 2006; Visser 2005; Stenseth 2002), and, therefore, may have implications for population success if the shift is not synchronous with food supply availability. Understanding where climate change-induced mistiming will occur and their underlying mechanisms will be critical in assessing the impact of global climate change on the success of migratory birds(Visser 2005). The responses across species will not be uniform across their ranges, and are thus likely to be highly complex and dependent on species-specific traits, characteristics of local microhabitats, and aspects of local microclimates.

A study of spring arrival and departure dates of 20 trans-Saharan migratory bird species to the United Kingdom found an 8-day advance in the arrival and the departure time to the breeding grounds, but with no change in the residence time. The timing of arrival advanced in relation to increasing winter temperatures in sub-Saharan Africa, whereas the timing of departure advanced in response to elevated summer temperatures in their breeding ground (Cotton 2003). But, without an understanding of how this change correlates with phenology of the food resource, it is difficult to discern what the long-term consequences might be (Visser 2005).

Mismatches and extinctions

Migratory birds have adapted their timing of reproduction to the timing of the food resources. A careful examination of food resource availability relative to spring arrival and egg-laying dates will aid in the understanding of impacts of climate change. There is a suite of responses that facilitate an adaptive phenological shift: a shift in egg-laying date or a shift in the period between laying of the eggs and hatching of the chicks. In a long-term study of the migratory pied flycatcher (*Ficedula hypoleuca*), researchers found that the peak of abundance of their food resource (caterpillars) has advanced in the last two decades and, in response, the birds have advanced their laying date. In years with an early caterpillar peak, the hatching date was advance and the clutch sizes were larger. In this case, populations of the flycatcher have declined by about 90 percent over the past two decades in areas, where the food for provisioning nestlings peaks early in the season but not in areas with a late food peak (Both 2006). Climate change will lead to changing selection pressures on a wide complex of traits (Both 2005). It is the mistiming of the migration arrival, the provisioning of food resources and the lay dates that drive population declines. Predicting the long-term effects of ecological constraints and interpreting changes in life-history traits requires a better understanding of both adaptive and demographic effects of climate change. Exploring the risk of extinction of populations empirically related to parameters characterizing population dynamics for a set of 38 bird populations, environmental stochasticity had the most immediate effect on the risk of extinction (Saether 2005), whereas the long-term persistence of the population was most strongly affected by the specific population growth rate. Research focused on both will aid in the understanding of the impacts of climate change.

5.3.2 Butterflies

Since temperature determines timing of migration and distribution, it is not surprising that many studies have documented changes in phenology of migration and significant shifts in latitudinal and elevational distribution of butterflies in response to current day warming (cite). The migration of butterflies in the spring is highly correlated with spring temperatures and with early springs. Researchers have documented many instances of earlier arrivals (26 of 35 species in the United Kingdom, (Roy 2000); 17 of 17 species in Spain, (Stefanescu 2004); and 16 0f 23 species in central California (Forister 2003). An analysis of 113-year record of nine migrating butterflies, and 20 migrating moths found increasing numbers of migrants with increasing temperature along the migration route in response to fluctuation in the North Atlantic Oscillation (Sparks 20059).

Butterflies are also exhibiting distributional and/or range shifts in response to warming. Across all studies included in her synthesis, Parmesan (2006) found 30-75 percent of species had expanded northward, less than 20 percent had contracted southward, and the remainder were stable (Parmesan 2006). In a sample of 35 non-migratory European butterflies, 63 percent have ranges that have shifted to the north by 35-240 km during this century and three percent have shifted to the south (Parmesan 1999). In North America, butterflies are experiencing both distributional shifts northward, with a contraction at the

southern end of their historical range, and to higher elevations as climate changes. In a 1993-1996 recensus of Edith's checkspot butterfly (*Euphydryas editha*) populations, Parmesan et al. (1996) found that 40 percent of the populations below 2400 feet had become extinct despite the availability of suitable physical habitat and food supply, compared to only 15 percent extinct above the same elevation (Parmesan, 1996). An investigation of a skipper butterfly (*Atalopedes campestris*) found that 2-4°C warming had driven the northward range expansion over the past 50 years, driven by increases in winter temperatures (Crozier 2003, 2004). A study investigating the altitudinal and latitudinal movements of 51 British butterfly species related to climate warming found that species with northern and/or montane distributions have disappeared from low elevation sites, and colonized sites at higher elevations consistent with a climate warming, but found no evidence for a systematic shift northwards across all species (Hill 2002). A subsequent modeling exercise to project potential future distributions for the period 2070-2099 projects 65 and 24 percent declines in range sizes for northern and southern species, respectively (Hill 2002).

Mismatches and Extinctions

Like birds, changes in timing of migrations and distributions are likely to present resource mismatches that will influence population success and alter the probability of extinction. Predictions of climate-induced population extinctions are supported by geographic range shifts that correspond to climatic warming and a few studies have linked population extinctions directly to climate change. As populations of butterfly species become isolated by habitat loss, climate change is likely to cause local population extinctions. Modeling of butterfly distribution in the future under climate change found that while the potential existed to shift ranges northward under in response to warming, lack of habitat availability caused significant population declines (Hill 2002). Similarly, phenological asynchrony in a butterfly-host interactions in California led to population extinctions of the checkerspot butterfly (*E. editha*) during extreme drought and low-snowpack years (Singer, 1996; Thomas 1996; Ehrlich 1980; Singer, 1979). A modeling experiment of two populations of a checkerspot butterfly, suggested decline of the butterfly was hastened by increasing variability in precipitation associated with climate change. The changes in precipitation amplified population fluctuations leading to extinction in a region that allowed no distributional shifts because of persistent habitat fragmentation (McLaughlin 2002).

Evolutionary change
A study of the speckled wood butterfly (*Pararge aegeria*) in England, found evolutionary changes in dispersal were associated with reduced investment in reproduction, which affect the pattern and rate of expansion at range boundaries (Hughes 2003).

5.3.3 Wildlife and population contractions

5.3.3.1 Mammals

Mammals are likely to interact with climate through indirect pathways involving their food source, habitat and predators, perhaps more strongly than through direct effects on body temperature (Schneider and Root 2002). Climate change will likely alter the distribution and abundance of northern mammals through a combination of direct, abiotic effects (e.g., changes in temperature and precipitation) and indirect, biotic effects (e.g., changes in the abundance of resources, competitors, and predators).

5.3.3.2 Amphibians

There is evidence that amphibian breeding is occurring earlier in some regions, and that global warming is likely the driving factor.(Beebee 2002; Blaustein 2001; Gibbs 2001). Some temperate-zone frog and toad populations show a trend toward breeding earlier, whereas others do not (Blaustein 2001). Statistical tests (Blaustein 2002) indicate that half of the 20 species examined by Beebee (1995), Reading (1998), Gibbs and Breisch (2001), and Blaustein et al. (2001) are breeding earlier. Of the half not exhibiting statistically significant earlier breeding, they are showing biologically important trends toward breeding earlier that, if continued, will likely become statistically significant (Blaustein 2002). When taken together, these important data suggest that global warming is indeed affecting amphibian breeding patterns in many species.

There is marked unevenness of climate-change effects on amphibian breeding. For example, *Bufo fowleri*, a late breeder, has bred progressively later in spring over the past 15 years on the north shore of Lake Erie (Blaustein 2001)

5.3.3.3 Mismatches and extinctions

5.3.3.4 Evolutionary change

5.4   Climate drivers (secular changes, changes invariability)

5.5   Impacts on services *<incomplete>*

Climate change and variability is very likely to have impacts on an array of ecosystem services in the United States in a variety of ways (cite).

Recreational services

A changing climate and its impact on biodiversity will impact recreational services in the United States (cite). The United States has a $112 billion international tourism market and domestic outdoor recreation market (World Trade Organization 2002; Southwick Associates 2006).

Pollination services

5.5.1 Needs

The ability of biologists to anticipate biotic responses is limited to some degree by lingering uncertainty on how regional climates will be affected by the complex, interactive effects of global changes in temperature, precipitation, and circulation patterns (IPCC 2007 FAR; Houghton 2001). But greater uncertainty lies in how species and their communities will respond. Temperature and seasonality are so fundamental to our understanding of the organization of biological communities, that further investigation of their effects can provide biological insights quite independent of issues related to climate change.

For insight into how climate change and variability over the next 40 years may impact species' phenologies and ranges, one can look at the affect that the PDO has had on ecological systems over the past few decades. By using time series of climatic indices and parameters of species populations, complex relationships between species and climate, researchers may be able to develop a deeper understanding of the ecological significance of the interactions

5.6   Changes in Coastal and Near Shore Ecosystems (focusing on the United States)

Coastal and marine ecosystems have been the location of some of the most dramatic effects of climate change to date. In the tropics, coral bleaching and disease events have increased, and storm intensity has increased; in temperate regions, there are demonstrated range shifts and possible alterations of ocean currents and upwelling sites; and in the Arctic, there have been dramatic reductions in sea ice extent and thickness, as well as related coastal erosion. Marine species were the first to be listed as threatened species due to the effects of climate change. Coastal and near-shore ecosystems are vulnerable to a host of climate change-related effects, including increasing air and water temperatures, ocean acidification, altered terrestrial run-off patterns, altered currents, sea level rise, and altered human pressures due to these and other related changes (such as development, shipping, pollution, and adaptation strategy implementation).

This section will discuss some of the most prominent effects of climate change we have seen to date in the coastal and near-shore regions of the United States.

5.6.1 Coral Reefs

The United States has extensive coral reef ecosystems in both the Caribbean Sea and the Pacific Ocean. Coral reefs are very diverse ecosystems, home to a complex of species that support both local and global biodiversity and human societies. It has been estimated that coral reefs have a $30 billion value (Cesar et al. 2003). Corals and tropical regions where they live are experiencing increasing water temperatures, increasing storm

intensity (Emmuel 2005), and a reduction in pH (Ravens et al. 2005), all while experiencing a host of other ongoing challenges from development/tourism, fishing, and pollution. The effects of climate change in marine systems is highlighted by the 2006 listing as Threatened under the Endangered Species Act of two species of corals in the Caribbean (Federal Register 2006). The major threats that motivated the listings of Elkhorn (*Acropora palmata*) and Staghorn (*A. cervicornis*) corals were disease, elevated sea surface temperatures, and hurricanes – all of which relate to climate change.

Increasing Temperature

The El Niño-Southern Oscillation (ENSO) event of 1982-83 marked the first contemporary broad-scale coral reef bleaching and mortality event (Glynn 1984). Since then, there have been subsequent bleaching events including the 1997-98 ENSO. The rate of occurrence (annually in some cases), and almost global scale since the early 1980s is in stark contrast to the trend of the first half of the century in which bleaching events were localized and linked to local events (D'Elia 1991; Glynn 1993). From 1876-1979 only three bleaching events were recorded, whereas 60 are on record between 1980 and 1993 (Glynn 1993). Bleaching is considered to be a stress response caused primarily by increased water temperature (Glynn 1993) and synergistically enhanced by increased irradiance levels (Fitt and Warner 1995; Jokiel and Coles 1990; Lesser et al. 1990). Corals become stressed if exposed to slight increases in water temperature – temperatures need only increase by 1 to 2ºC over the average annual thermal maxima for days to weeks to result in a bleaching event (Hoegh-Guldberg 1999). Field studies have correlated increased temperatures with mass bleaching events (Brown 1997; Hoegh-Guldberg et al. 1997; Glynn 1993). Additionally, the National Oceanic and Atmospheric Administration (NOAA) "Hotspot" program (Goreau and Hayes 1994) predicted bleaching for most geographic regions where bleaching occurred in 1998, adding further weight to the assessment that elevated temperature is the primary trigger for bleaching (Hoegh-Guldberg 1999).

In 2005, the Caribbean basin saw unprecedented water temperatures and some very dramatic bleaching, followed by coral disease and mortality. The most dramatic monitored bleaching took place in the U.S. Virgin Islands, where National Park monitoring showed that at some sites 90 percent of the coral bleached. Then there appeared to be a period of recovery as water temperatures decreased. Unfortunately, this was short-lived as disease appeared in November on many of the previously bleached corals. To date there is an estimated 50 percent combined mortality from bleaching and disease in the Virgin Island National Park surveys. As of yet, there are no reports of recovery as amounts of mortality continue to increase (Eakin et al. In Prep). In the Florida Keys, equally massive bleaching was seen as imminent when temperatures exceeded nine-degree heating weeks in late August 2005 (NOAA Coral Reef Watch), and some bleaching was seen. But the arrival of Hurricanes Katrina and Rita reduced water temperatures and seemed to have provided some respite for corals in the Keys. However, the same pattern of disease was seen in the Keys in those corals that did bleach, with bleaching setting in around mid-August, followed by disease in early September (Brandt In Prep).

Additionally as CO_2 concentrations increase in the atmosphere, more CO_2 is absorbed by the world's oceans. During the past 200 years, there has been a 30 percent increase in hydrogen ion concentration in the oceans and it is anticipated that this will increase by 300 percent by the end of this century (Ravens et al. 2005). There are predictions that oceans could become too acidic for corals – as well as other species – to produce calcium carbonate skeletons (Caldeira & Wickett 2003; Hoegh-Guldberg 2005; Kleypas et al. 1999).

Increasing sea surface temperatures are expected to continue as global temperatures rise. It is possible that these warmer waters are also increasing the intensity of the tropical storms in the region (Mann and Emmanuel 2006; Sriver and Huber 2006; Elsner 2006; Hoyos et al. 2006). As global temperatures rise, sea level will continue to rise providing additional challenges for corals. Increasing depths change light regimes and inundated land will potentially liberate additional nutrients and contaminants from terrestrial sources, especially agricultural and municipal.

5.3.1 Coastal Seashores

Some of the most valuable property in the United States is that located along seashores. This land is also vitally important for biodiversity as many species use the marine/terrestrial interface, including many endangered species such as sea turtles and sea birds. Projections for sea level rise by 2100 vary from 0.18 to 0.59 meters (±0.1-0.2) (IPCC 2007) to 0.5 to 1.4 m (Rahmstorf 2007). It has been estimated that a one-meter increase in sea level would lead to the loss of 65 percent of the coastal marshlands and swamps in the contiguous United States (Park et al. 1989). In addition to overt loss of land, there will also be shifts in "quality" of habitat in these regions. Prior to being inundated, coastal watershed will become more saline due to saltwater intrusion into both surface and groundwater.

Climate change will also lead to increasing coastal erosion through several processes, such as increasing coastal storm intensity, shifts to fewer more intense storm events in some regions and loss of sea ice cover during traditional storm seasons. While these issues have been well addressed in terms of human infrastructure and settlement vulnerability to climate change, they have been less well explored in terms of biodiversity. However, this will be a growing challenge for species that rely on coastal space or services for reproduction and feeding.

Some of this coastal habitat is on remote barrier islands, where the vulnerability to sea level rise is acute. In the Northwest Hawaiian Islands, recently made a National Monument, sea level rise is a threat to endangered beach nesting species and island endemics, including green sea turtles, Hawaiian monk seals, and the Laysan finch (Baker et al. 2006). Another example of an endangered island-locked species is the Key Deer, which is now limited to living on two islands in the Florida Keys. Their habitat is also at risk with most of the Keys at less than two meters above sea level. Median sea level rise

coupled with storm surges would inundate most of the available habitat either
permanently or episodically, either way further threatening this endangered species.

5.3.2 Arctic

Changes in the Arctic are resulting in substantial shifts in habitat, especially for sea ice-dependent species, where it is literally melting away. The sea ice, which provides habitat both below and above the ocean, has been in retreat for at least 30 years (Stroeve et al. 2005; Rothrock et al. 2003). It is estimated that a summer-ice-free Arctic Ocean is likely by the end of the century (Overpeck et al. 2005), with some models suggesting that this could occur as soon as 2040 (Holland et al. 2006).

Ice loss to date is already causing measurable changes in polar bear and ringed seal populations and fitness (Derocher et al. 2004; Ferguson et al. 2005; Stirling et al. 1999). There are also shifts in species ranges in the Arctic, both on land and in the water, and changes in phenology.

Many impacts are seen in coastal and near-shore ecosystems around the planet:

- Range shifts and phenological changes – Fish and planktonic species distribution in marine ecosystems are predominately determined by climatic variables (Hays et al. 2005; Roessig et al. 2004) and there is already evidence that marine species are moving poleward, and that timing of plankton blooms is shifting (Beaugrand et al. 2002; Hays et al. 2005; Richardson & Schoeman 2004). Similar patterns are seen with invertebrates and marine plants (CITATIONS).
- Invasive Species – Climate change will challenge thinking about invasive species as ranges shift and species are seen in new, but likely adjacent locales. Although most of the research beind done relates to terrestrial systems, those species more traditionally thought of as invasive species – i.e. more cosmopolitan species better adapted to dealing with a range of environmental parameters, especially temperature – are expected to have a competitive advantage as there is greater environmental variability and warming thermal regimes (Dukes and Mooney 1999; Carlton 2000).
- Mangroves and Sea Grasses – These coastal plants are found in tropical and temperate coastal regions around the world and both are already greatly degraded from other anthropogenic causes (CITATION). It has only been in recent years that their true value to coastal ecosystems was fully appreciated. Unfortunately climate change is expected to further compound their degradation. Mangroves will struggle as sea level rises, coastal storm-intensity increases, and terrestrial hydrological regimes change. Many sea grass species have limited thermal tolerances. In the Chesapeake Bay, for example, the dominant sea grass species (*Zostera marina*) is thought to be reaching its thermal maximum (Short and Neckles 1999), and this is playing a part in its decline.
- Currents and upwelling are expected to change as a result of climate change. Increased stratification and stability of the water column due to surface water

1   warming can result in upwelling reductions, both near-shore and open-ocean
2   (summarized in Soto 2002; Field et al. 2001). Decreased upwelling can decrease
3   nutrient input to surface waters, reducing primary productivity. The food-web-
4   level effects that such changes cause have been documented off the coast of
5   Southern California following an abrupt and sustained increase in water
6   temperature in the 1970s (reviewed in Field et al. 1999). Conversely, climate
7   change may alter wind patterns in ways that increase offshore winds and thus
8   upwelling (Bakun 1990). Additionally there may be altered current regimes
9   including reduction in area and a coastward migration of shelf-tidal fronts, a
10   reduction in strength of the Gulf Stream, and an increase in strength of the
11   Labrador Current (Soto 2002). These changes will affect nutrient availability,
12   species distribution and in some cases weather patterns.

13 *5.4 Changes in Pests and Pathogens*

14 **5.4.1 Interactions of climate change with pests, pathogens, and invasive**
15 **species**

16
17 Increasing temperatures and other alterations in weather patterns (e.g., drought, storm
18 events) resulting from climate change are likely to have significant effects on outbreaks
19 of pests and pathogens in natural and managed systems, and are also expected to facilitate
20 the establishment and spread of invasive alien species (IAS). Initially, the most noticeable
21 changes in plant and animal communities will most likely result from direct effects of
22 climate change (for example, range expansions of pathogens, and invasive plants). The
23 longer term consequences, however, may be the result of indirect effects such as
24 disruptions of trophic relationships or a species decline due to the loss of a mutualistic
25 relationship (Parmesan 2006).
26
27 Interactions between increasing global temperature and pests and pathogens are of
28 particular concern because of the rapid and sweeping changes these taxa can render.
29 While it is still difficult to predict specifically how climate change will interact with
30 insect pests, or plant and animal diseases, some recent events have provided glimpses
31 into the kinds of impacts that might unfold.

32 *5.4.4.1 Mountain Pine Beetle Explosion*

33
34 The mountain pine beetle (*Dendroctonus ponderosae*) is a native species that has co-
35 existed with western conifers for thousands of years, and plays an important role in the
36 life cycle of western forests (Powell and Logan 2001). However, the magnitude of recent
37 outbreaks is above historical levels and record numbers of Colorado's lodgepole pine
38 (*Pinus contorta*) are being killed. For example, a recent outbreak caused the death of
39 nearly five million lodgepole pines in Colorado in 2006, a four-fold increase from 2005.
40 The infestation covers nearly half of all Colorado's forests. Such outbreaks are not
41 confined to Colorado, but are also occurring in other parts of the United States and
42 Canada, affecting tens of thousands of square miles of forest (http://cfs.nrcan.gc.ca/).
43

A great deal of attention has been given to the role of climate change in these outbreaks, but some researchers are cautious about designating global warming as a causal factor (e.g., Romme et al. 2006). Several simultaneously occurring factors appear to explain the outbreaks. First, Colorado's lodgepole pines are primarily mature even-aged stands due to heavy logging of the region during settlement 100 years ago. Mountain pine beetles utilize mature trees and therefore they have an abundant food source. Second, long-term drought stresses trees and makes them more vulnerable to the beetles because they cannot effectively use their sap to defend themselves. Third, warmer summers provide additional stress and may increase growth rates of the insects, and, fourth, milder winters increase the chances of survival for the insect larvae (Romme et al. 2006). While there is not yet definitive proof that climate change is behind the high levels mountain pine beetle infestation, a recent study showed that over the last century Colorado's average temperatures have warmed (NRC 2007). It is therefore reasonable to expect warmer temperatures in the future may lead to similar or more intensive events than those that are now occurring.

5.4.1.2 Poleward migration of plant pests and pathogens

Latitudinal gradients in plant defenses and herbivory are widely accepted but the basis for these defenses (i.e., genetic versus environment) are not fully understood. A potential outcome under warming global temperatures is a relatively rapid poleward migration of pests and pathogens, and a relatively slower rate of adaptation (e.g., increased defense against herbivory) for plants. Biogeographic theory predicts increased insect herbivory (i.e. greater loss of leaf area to herbivores) in the lower latitudes relative to higher latitudes (MacArthur 1972; Vermeij 1978; Jablonski 1993). As with the mountain pine beetle described above, higher population densities of other herbivorous insects and therefore herbivory occur because dormant season death (i.e., winter dieback) of herbivores is absent, or greatly reduced at warmer temperatures, and/or plant productivity is generally greater than at higher latitudes (Coley and Aide 1991; Coley and Barone 1996). Because of this greater herbivory, plants are thought to be better defended or otherwise less palatable at low latitudes as a result of natural selection (e.g., MacArthur 1972; Hay and Fenical 1988; Coley and Aide 1991; Coley and Barone 1996). Alternatively, plants at low latitudes could be better defended because high latitude populations have had fewer generations since the last glaciation to evolve such defenses (Fischer 1960).

5.4.1.3 Climate Change and Pathogens

Evidence is beginning to accumulate that links the spread of pathogens to a warming climate. For example, the chytrid fungus (*Batrachochytrium dendrobatidis*) is a pathogen that is rapidly spreading world-wide, and decimating amphibian populations. A recent study by Pounds and colleagues (2006) showed that widespread amphibian extinction in the mountains of Costa Rica is positively linked to global climate change. To date, geographic range expansion of pathogens related to warming temperatures has been the most easily detected (Harvell et al. 2002), perhaps most readily for arthropod-borne infectious disease (Daszak et al.). However, a recent literature review found additional

evidence gathered through field and laboratory studies that support hypotheses that latitudinal shifts of vectors and diseases are occurring under warming temperatures. Based on their review, Harvell et al. (2002) gathered evidence that:

- Arthropod vectors and parasites die or fail to develop below threshold temperatures
- Rates of vector reproduction, population growth, and biting increase (up to a limit) with increasing temperature; and
- Parasite development rates and period of infectivity increase with temperature.

Furthermore, Ward and Lafferty (2004) conducted an analysis that revealed that disease for some groups of marine species is increasing while others are not. Turtles, corals, mammals, urchins, and mollusks all showed increasing trends of disease, while none were detected for sea grasses, decapods, or sharks/rays. The authors note that the effects of increasing temperature on disease are complex, and can either increase or decrease disease depending on the pathogen. Nonetheless, the stress of increased temperatures may cause susceptibility of marine and terrestrial organisms to pathogens to increase, ultimately making outbreaks more frequent (Ward and Lafferty 2004).

It is important to note, however, that a range expansion of an invader may not always be simply explained by pointing to warming temperatures. For example, the northern expansion of the invasive European green crab (*Carcinus maenas*) in North America, from the Gulf of Maine to Cape Breton, Nova Scotia, was thought to have occurred because of warming sea temperatures, and/or adaptations of established more southerly populations to colder northern waters (Roman 2006). However, the application of molecular techniques to green crab populations in U.S. and Canadian waters revealed that introduction of new lineages of *C. maenas* to Nova Scotia from the northern end of its native range in Europe was more likely. These northern populations may be better adapted to the colder temperatures found in northern Nova Scotia, relative to more southerly waters (Roman 2006). Furthermore, the construction of a causeway and subsequent "super port" in the Strait of Canso, Nova Scotia, appear to be at the epicenter of the high diversity of new *C. maenas* haplotypes (Roman 2006).

5.4.1.4 Climate change and invasive plants

Projected increases in CO_2 are expected to stimulate the growth of most plants species, and some invasive plants are expected to respond with greater growth rates than non-invasive plants (Dukes 2000; Ziska and George 2004; Moore 2004; Mooney et al. 2006). Some invasive plants may have higher growth rates, greater maximal photosynthetic rates relative to native plants under increased CO_2, but definitive evidence of a general benefit of CO_2 enrichment to invasive plants over natives has not emerged (Dukes and Mooney 1999). Nonetheless, invasive plants in general may better tolerate a wider range of environmental conditions and may be more successful in a warming world because they can migrate and establish in new sites more rapidly than native plants, and they are not usually limited by pollinators or seed dispersers (Vila et al. In Press).

Finally, it is critical to recognize that other elements of climate change (e.g., nitrogen deposition, land conversion) will play a significant role in the success of invasive plants in the future, either alone or under elevated CO_2 (Vila et. al. In Press). For example, several studies have brought to light the role of increasing nitrogen availability and the success of invasive grass species (e.g., Huenneke et al. 1990; Brooks 2003). Disturbance at both global and local scales has been shown to be an important factor in facilitating species invasions (e.g., Sher and Hyatt 1999; Mooney and Hobbs 2001; D'Antonio and Meyerson 2002) and land conversion that occurred more than 100 years may play a role current invasions (Von Holle and Motzkin 2007). Interestingly, recent work by Hierro et al. (2006), which compared the effects of disturbance on *Centaurea solstitialis* in its native and introduced ranges, suggests that disturbance alone does not fully explain invasion success. Instead, it appears that, for *C. solstitialis,* it is the combination of disturbance and escape from soil pathogens in the native range that has encouraged invasion.

5.5 Climate change, marine fisheries and marine ecosystem change

The IGBP- GLOBEC program (GLOBal Ocean ECosystem Dynamics) was established in the early 1990s to investigate the potential impacts of global climate change on marine ecosystems. National programs were established in Europe (United Kingdom, France, Norway, Germany, Netherlands, Spain, Portugal, Italy, Turkey, and the Ukraine), North America (United States, Canada, and Mexico), South America (Peru, Chile, and Brazil) and the Far East (Japan, Korea, and China). The emphasis of all of these programs was on the coupling between physical forcing and biological responses in fisheries-rich ecosystems. All programs included long-term modeling and observation programs, as well as focused process studies. One of the challenges each program faced was that of unraveling the causes of recent changes in fisheries stocks to determine to what degree stock declines were due to fishing itself versus changes due to climate forcing? It was with varying degrees of success that each program was able to sort out these (sometime confounded) effects on fisheries. Regardless, clear linkages between climate variability, zooplankton (the forage base for many fisheries), and some fish stocks have been established by many of the GLOBEC national programs. Results shown below are the result of long time series of measurements of physical and biological variables. Without time series of ocean observations, study of impacts of climate variability on marine ecosystems would be far more difficult.

Climate Regime Shifts. It has been well established that the large, basin-scale atmospheric pressure systems that drive basin-scale winds can suddenly shift their location and intensity at decadal time scales, with dramatic impacts on winds and ocean circulation patterns. These low frequency oscillations are known as the North Atlantic Oscillation (NAO) and the PDO. Perhaps the greatest discovery of the past 10 years is that these shifts have dramatic impacts on marine ecosystems. The NAO, first discovered in the 1920s by Sir Gilbert Walker**,** refers to the fluctuations in the difference of atmospheric pressure between the Icelandic Low and the Azores High; these fluctuations control the strength and direction of westerly winds and storms across the North Atlantic. The NAO is one of the most important drivers of climate fluctuations in the North

1 Atlantic and surrounding continents. When the NAO is in positive phase, stronger than
2 normal westerly winds blow across the Atlantic, bringing moist air into Europe, resulting
3 in cool summers, and mild winters with heavier, more frequent rainfall. When in negative
4 phase, westerly winds are weaker than normal, temperature are more extreme in summer
5 and winter, leading to heat waves, deep freezes, and reduced rainfall.

6 The NAO was in positive phase from 1910-1935, negative from 1935-1975, but then
7 positive since 1975. It has been strongly positive since the 1980s. Increases in the
8 strength of the winds, initiated in the late 1980s, resulted in dramatic impacts on
9 Northeast Atlantic ecosystems. Examples include increased flow of oceanic water into
10 the English Channel and North Sea, resulting in a northward shift in the distribution of
11 zooplankton such that the zooplankton community became dominated by warm water
12 species (Beaugrand 2004), with concomitant changes in fish communities from one
13 dominated by whiting (hake) to one dominated by sprat (similar to a herring). Similar
14 (and drastic) ecosystem changes are known for the Baltic Sea (Kenny and Mollman
15 2006), where dramatic changes in both zooplankton and fish communities were observed.
16 Cod were replaced by sprat, and dominance in zooplankton switched from lipid-rich (and
17 high bioenergetic content) species to lipid-poor species. Linkages between the NAO,
18 zooplankton and fisheries have also been described for the Northwest Atlantic waters off
19 eastern Canada and the United States. Pershing and Green (2007) report a decrease in
20 salinity, and an increase in biomass of small copepods (zooplankton). They suggest that
21 the recovery of the codfish populations, which collapsed in the early 1990s (presumably
22 as a result of overfishing), may continue to be difficult due to negative changes in food
23 chain structure of their forage base, the zooplankton.

24 In the North Pacific, the PDO refers to the east-west shifts in location and intensity of the
25 Aleutian Low in winter (Mantua et al. 1997). When the PDO is in negative phase, the
26 Aleutian Low sits over the western Pacific and is relatively weak; in positive phase it is
27 centered over the Gulf of Alaska and has very deep low pressure. Shifts in location of the
28 Aleutian Low results in changes in wind speed and direction and storm tracks. When in
29 negative phase, winter winds tend to be more northerly, and winters are drier, whereas in
30 positive phase, winter winds are usually southerly, and winters are wet. Changes in sign
31 of the PDO have been noted in 1925 (to positive phase), 1947 (to negative phase), and
32 1977 (to positive phase).

33 Widespread ecological changes have also been discovered, including increased
34 productivity of the Gulf of Alaska when the PDO is in positive phase, resulting in
35 dramatic increases in salmon production (Mantua et al. 1997), and a reversal of demersal
36 fish community dominance – from a community dominated by shrimps to one dominated
37 by pollock (Anderson and Piatt, 1991). Associated changes to the California Current
38 ecosystem include dramatic decreases in zooplankton (McGowan et al. 1998) and salmon
39 (Pearcy 1991) when the PDO changed to positive phase in 1977. Recently the sign
40 changes have occurred with a higher frequency: cool phase from 1999-2002 (Peterson
41 and Schwing 2003) was interrupted by four year of warm phase (2003-2006).
42 Zooplankton and salmon responded rapidly and positively to the switch to cool phase in
43 1999: the zooplankton changed to a cold-water community and salmon returns increased

1 by nearly an order of magnitude. However, with the switch to warm phase in 2003,
2 zooplankton and salmon populations collapsed (see
3 http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm.

4 One of the most intriguing problems that GLOBEC programs in the Pacific investigated
5 was that of understanding the causes of cycles in sardine and anchovy populations in the
6 Pacific Ocean. There is also evidence that the large osciallations in abundances of sardine
7 and anchovy populations are associated with PDO shifts, such that during positive
8 (warm) phase, sardine stocks are favored but during negative (cool) phase, anchovy
9 stocks dominate (e.g., Chavez et al. 2003).

10 **El Niño Events**. Another major driver of climate variability is the El Niño – Southern
11 Oscillation (ENSO). The ENSO affects rainfall patterns in the South America and the
12 Southeastern U.S. (causing droughts during La Niña events and excess rainfall during El
13 Niño events). El Niño events also wreck havoc on zooplankton and fish stocks from
14 Chile, north to Peru, then across the equator to Mexico, the United States, and Canada.
15 Plankton and fish stocks collapse due to sudden warming of the waters (by 4 to 10°C), as
16 well through poleward advection of tropical species into temperate zones. Impacts of
17 ENSO activity is well-known and well-studied and is probably beyond the scope of this
18 brief overview.

19 **Warming and acidification**. It has recently been noted that a general warming of the
20 oceans is stressing coral reefs, particularly in the tropical Pacific; also, recent reports are
21 suggesting that increases in CO_2 concentration are lower ocean pH, an additional stressor
22 on coral reefs (Orr et al. 2005). Again, as with ENSO, this is a huge topic, that cannot be
23 adequately reviewed here.
24
25 **Other climate-driven physical forces that affect marine ecosystems**. The following is
26 only a listing of some of the problems that marine organisms are likely to face with
27 continued global warming. The listing reflects processes that are likely to change
28 significantly for waters of the northern California Current (off the Pacific Northwest),
29 and is drawn from a document in preparation by the National Marine Fisheries Service
30 that is summarizing potential impacts of global warming and climate change on the
31 nation's fisheries of the US Exclusive Economic Zone (EEZ):
32
33 The California Current (CC) is designated by NOAA as one of eight "Large Marine
34 Ecosystems" (LME) within the United States EEZ. However, one should not view the
35 CCLME as a homogenous body of water, which contains one "large" ecosystem because
36 the current is typified by latitudinal gradients in both physical forcing and biological
37 response. The northern end of the current is dominated by strong seasonal variability in
38 winds, temperature, upwelling, plankton production and the spawning times of many
39 fishes, whereas the southern end of the current has much less seasonal variability in these
40 parameters. For planktonic organisms and some fish species, the northern end of the
41 Current is dominated by sub-arctic boreal fauna, whereas the southern end is dominated
42 by tropical and sub-tropical species. Faunal boundaries, i.e., regions where rapid changes
43 in species composition are observed, are known for the waters between Cape Blanco

1 Oregon/Cape Mendocino California, and in the vicinity of Point Conception California.
2 Higher trophic-level organisms often take advantage of the strong seasonal cycles of
3 production in the north by migrating to northern waters during the summer to feed.
4 Animals that exhibit this behavior include pelagic seabirds, such as black-footed albatross
5 and sooty shearwaters, fishes such as Pacific whiting and sardines, and gray and
6 humpback whales
7
8 Climate and ecosystem studies in the North Pacific have been assigned a high priority by
9 NOAA because climate signals in this region are quite strong. During the past 10 years,
10 the North Pacific has seen two El Niño events (1997/98 2002/03), one La Niña event
11 (1999), a four-year climate regime shift to a cold phase from 1999 until late 2002,
12 followed by a four-year shift to warm phase from 2002 until 2006. The response of ocean
13 conditions, plankton and fish to these events is well documented in the scientific
14 literature. The biological responses are often so strong that the animals themselves often
15 give early warning of impending events and may be more capable of providing early
16 indications of climate change than projections made purely from physical variables.

5.5.1 Observed and Projected Impacts

19 Based on long-term observation records, global climate models, regional climate models,
20 and first principles, there is a general consensus on the following scenarios of climate
21 change for the northern California Current:

23 • Snowpack & Rainfall – Warmer air temperatures will result in more precipitation
24 and less snowpack per unit of precipitation. Potential changes in rainfall and
25 snowpack, for example, are likely to increase winter and spring runoff but
26 decrease summer runoff. The current system of hydropower generation and water
27 storage will become less suitable to this changed pattern, but capital investments
28 in the system can mitigate some of those effects. This may change the way the
29 freshwater of the Columbia and Sacramento Rivers is managed, which in turn
30 may affect the way salmon and estuarine-dependent species are managed.

32 • Increased Water Temperature – Warmer water temperatures will also affect
33 freshwater salmon habitats, by reducing habitat opportunity on both spatial and
34 seasonal time scales. In oceanic habitats, the southern boundaries of salmon
35 habitat will likely shift northward.

37 • Water Column Stratification – Warmer air temperatures may lead to increased
38 stratification of the coastal waters off the Pacific Northwest as well as the Gulf of
39 Alaska; moreover, increased melting of glaciers in the Gulf of Alaska, coupled
40 with warmer sea surface temperatures will result in increased stratification of the
41 Gulf. Since some of the source waters that supply the northern California Current
42 (NCC) originate in the Gulf of Alaska, more stratified source waters will
43 contribute to increased stratification of coastal waters of the NCC.

45 • Freshwater Input – Climate models project the 21st century will feature greater

annual precipitation in the Pacific Northwest, extreme winter precipitation events in California, and a more rapid spring melt leading to a shorter, more intense spring period of river flow and freshwater discharge. This will greatly alter coastal stratification, plume formation and evolution, and the transport of anadramous populations.

- Upwelling Winds – Coastal upwelling may become stronger due to greater contrasts between heating of the land (resulting in low atmospheric pressure) and heating of the ocean. That is, soils heat much faster than water thus we will have deeper lows over land in summer and higher highs over the ocean, resulting in higher wind speeds and the potential for more upwelling.

- Upwelling of Nutrient-rich Water – Even though northward winds that cause coastal upwelling are likely to increase in magnitude, we do not know if these winds will be able to over-ride increased water column stratification. That is, the winds may not be able to mix this light buoyant water or transport it offshore, resulting in the inability of the cold nutrient-rich water to be brought to the sea surface. Thus, phytoplankton blooms may not be as intense, and results will be transmittal of negative effects up the food chain.

- Shifts in Seasonal Cycles of Production – Should the increased-upwelling scenario prove to be true, then it is likely that the upwelling season will begin earlier and continue longer in each year. Animals that migrate within the California Current to take advantage of feeding opportunities associated with the seasonal cycle of production (such as whiting, sardines, shearwaters, loggerhead turtles, Grey Whales) may find that their migrations will have to be timed to an earlier arrival at the feeding grounds. Similarly, fish and sea birds whose spawning, breeding, or nesting coincides with peaks in seasonal cycles of production may have to make adjustments in the timing of such activities.

- Phytoplankton Species Composition – The long-term observations program in Monterey Bay is suggesting that as a result of increased stratification, the phytoplankton community is changing from one dominated by diatoms to one dominated by dinoflagellates. Although we do not know what impact this might have on zooplankton grazers, it is clear that diatoms are the primary source of lipids, which contribute to lipid- and energy-rich food chains. There is no similar information available from other regions of the California Current.

- Zooplankton Species Composition – Warm ocean conditions lead to a community of zooplankton that is subtropical in origin whereas cold water conditions result in a cold water community. The dominant cold-water zooplankton species are large lipid-rich species, which result in a food chain of higher bioenergetic content. The opposite case is also true – warm-water species are small and do not have high lipid reserves.

- Northward Shifts in Distribution – Generally warmer conditions will mean a

northward shift in the distribution of most pelagic species, and possibly the creation of reproductive populations in new regions. The existing faunal boundaries are likely to remain as strong faunal boundaries, but their resiliency to shifts in ocean conditions due to global climate change is not known. However, there is considerable heterogeneity in factors such as upwelling and climate along coastal regions that can complicate this generalized response for benthic species.

- Lower Productivity – It is generally accepted that the future climate will be warmer, and the upper ocean will be on average more stratified. This will make upwelling more difficult and lower primary productivity in the CC. In the northernmost regions, areas where production is light limited may see higher productivity.

- Greater Atmospheric and Oceanic Variability – One of the likely consequences of global climate change will be a more volatile climate with greater extreme events on intraseasonal-to-interannual scales. For the CC, this will mean more frequent and severe winter storms, with greater wind mixing, higher waves, and coastal erosion, and more extreme precipitation events and years, which would impact coastal circulation and stratification.

- ENSO – Some global climate models predict a higher frequency of El Niño events. If true, primary and secondary production will be greatly reduced in the northern California Current, with negative effects transmitted up the food chain.

- Decadal Variability (Regime Shifts) – Most models project roughly the same timing and frequency of decadal variability in the North Pacific under the impacts of global warming. However, combined with the global warming trend, the CC is likely to experience a greater frequency of years consistent with historical periods of lower productivity (e.g., positive PDO values). We know from ongoing observations that a positive PDO and warmer ocean result in dominance of small, warm-water zooplankton (which are lipid-depleted), which may result in food chains with lower bioenergetic content. By about 2030, it is expected that the *minima* in decadal regimes will be *above* the historical mean of the 20th century (i.e., the greenhouse gas warming trend will be as large as natural variability).

- Impacts on Humans in Coastal Communities – Humans derive ecosystem goods and services from the California Current. Predicting the effects of global climate change on human communities is complicated by the ability of humans to adapt to and mitigate those changes. If global climate change affects the location of commercial and recreation marine resources, for example, communities with locational advantages today are likely to suffer while other communities may gain those locational advantages. If the overall level of those resources falls, coastal communities as a whole are likely to experience negative effects. Also, sea level rise, will clearly impact development of coastal communities, particularly land developed in low-lying areas, and dock facilities.

- Surprises – All of the global climate models predict increased variability in physical forcing. That could translate into problems for living marine resources of the Pacific Northwest if the past three years are any guide. The summer of 2005 was characterized by a three-month delay to the start of the upwelling season resulting in a lack of significant plankton production until August (rather than the usual April-May time period). Thus, fish, birds, and mammals that relied upon plankton production occurring at the normal time experienced massive recruitment failure. In contrast, the summer of 2006 had some of the strongest upwelling winds on record, yet many species again experienced recruitment failure, in part because there was a one-month period of no winds (mid-May to mid-June) that occurred at the time when many bird and fish species are recruiting. The year 2007 experienced a very early transition to a summer state (February), but intense storms may have erased that signature. Regardless, the ocean has been very cold during the winter of 2006-2007, and plankton production this year could be very high. But will anomalous storms interrupt this potential? Are we in for another surprise this summer?

5.6 Particular Sensitive Systems

5.6.1 Impacts of climate change on montane ecosystems

Temperate montane ecosystems are characterized by cooler temperatures and often increased precipitation compared to surrounding lowlands. Consequently, much of the precipitation falls in the form of snow, which serves to insulate the ground from freezing air temperatures, stores water that will be released as the snow melts during the following growing season, and triggers vertical migration by animal species that can't survive in deep snow. Changes in historical patterns of snowfall and snowpack are predicted as a consequence of global climate change, in part due to changes in spatial patterns of precipitation, and in part due to the warming that will result in more precipitation falling as rain rather than snow (Beniston and Fox 1996; MacCracken et al. 2001). Areas that historically had most of their annual precipitation as snow are now seeing more of it as rain; documentation of this trend comes from the Sierra Mountains, where Johnson found from analysis of a 28-year dataset (Johnson 1998) that below 2400 meters, less snow is accumulating and it is melting earlier. Diaz et al. (2003) also reported that all the major continental mountain chains exhibit upward shifts in the height of the freezing level surface over the past three to five decades. Increased variation in precipitation and temperatures is also predicted by climate change models, and Johnson (1998) also found that "Higher elevations exhibit greater variability, with most stations accumulating more snow and melting earlier. This could be the result of warmer air masses having higher moisture contents."

In addition to the influences of global climate change, which could affect both precipitation and temperature, regional effects can be important. For example, in the

Colorado Rocky Mountains there are significant effects of the ENSO and North Pacific Oscillation (PDO) on winter precipitation. ENSO has also been shown to cause changes in freezing level in the American Cordillera (Diaz et al. 2003). Of course, all downstream water flows from headwaters in mountain areas are also affected by the variation in both timing and quantity of snowmelt (e.g., Karamouz and Zahraie 2004).

These environmental changes are also resulting in the disappearance of glaciers in most montane areas around the world. The changes in patterns and abundance of melt water from these glaciers have significant implications for the sixth of the world's population that is dependent upon glaciers and melting snowpack for water supplies (Barnett et al. 2005). Plant and animal communities are also affected as glaciers recede, exposing new terrain for colonization in an ongoing process of succession (e.g., for spider communities, see (Gobbi et al. 2006)). One group of organisms whose reproductive phenology is closely tied to snowmelt is amphibians, for which this environmental cue is apparently more important than temperature (Corn 2003). Hibernating and migratory species that reproduce at high altitudes during the summer are also affected by the ongoing environmental changes. For example, marmots are emerging a few weeks earlier than they used to in the Colorado Rocky Mountains, and robins are arriving from wintering grounds weeks earlier in the same habitats (Inouye et al. 2000). Species such as deer, bighorn sheep, and elk, which move to lower altitudes for the winter, may also be affected by changing temporal patterns of snowpack formation and disappearance.

The annual disappearance of snowpack is the environmental cue that marks the beginning of the growing season in most montane environments. Thus it is not surprising that flowering phenology has been advancing in these habitats (Inouye and Wielgolaski 2003), as well as others at lower altitudes, mirroring what is going on at higher latitudes (Wielgolaski and Inouye 2003). There is a very strong correlation between the timing of snowmelt, which integrates snowpack depth and spring air temperatures, and the beginning of flowering by wildflowers in the Colorado Rocky Mountains (e.g., Inouye et al. 2002, 2003). And for some wildflowers, there is also a strong correlation between the depth of snowpack during the previous winter and the abundance of flowers produced (Inouye et al. 2002; Saavedra et al. 2003). The abundance of flowers can have effects on a variety of consumers, including pollinators (Inouye et al. 1991), herbivores, seed predators, and parasitoids, all of which are dependent on flowers, fruits, or seeds.

An unexpected consequence of earlier snowmelt in the Rocky Mountains has been the increased frequency of frost damage to montane plants, including the loss of new growth on conifer trees, of fruits on some plants such as *Erythronium grandiflorum* (glacier lilies), and of flower buds of other wildflowers (e.g., *Delphinium* spp., *Helianthella quinquenervis*, etc.) (Inouye 2007). Although most of these species are long-lived perennials, as the number of years in which frost damage has negative consequences on recruitment increases, significant demographic consequences may result. These and other responses to the changing montane environment are predicted to result in loss of some species at lower altitudes, and migration of others to higher altitudes. Evidence that this is already happening comes from studies in both North America (at least on a latitudinal scale, Lesica and McCune 2004) and Europe (Grabherr et al. 1994). It is predicted that

1 some animal species may also respond by moving up in altitude, and preliminary
2 evidence suggests that some bumble bee (*Bombus*) species in Colorado have moved as
3 much as a couple of thousand feet over the past 30 years (J. Thomson, personal
4 communication).
5

5.6.2 Polar bears in a changing climate

7

8 Approximately 150,000 to 250,000 years ago, a lineage of brown bears (*Ursus arctos*)
9 diverged into the lineage that led to the brown bears found today in the Alexander
10 Archipelago of southeastern Alaska, and another that led to the polar bear (*Ursus*
11 *maritimus*) (Cronin et al. 1991; Talbot and Shields 1996; Waits et al. 1998). The latter
12 form evolved rapidly after colonizing the sea ice environment of the Arctic Ocean, and
13 had developed the distinctive morphology of modern polar bears by 20,000 to 40,000
14 years ago (Stanley 1979; Talbot and Shields 1996). The bears' invasion of this novel
15 environment was stimulated by an abundance of seals, which had colonized the region
16 earlier in the Pleistocene (Demǎrǎ et al. 2003; Lister 2004). Adapting to the sea ice
17 environment and a dependence on seals – especially ringed seals (*Pusa hispida*) – exerted
18 strong selection on the morphology, physiology, and behavior of polar bears.
19
20 Morphological adaptations to the sea ice environment include dense, white fur over most
21 of the body (including between foot pads), with hollow guard hairs; short, highly curved
22 claws; and dentition specialized for carnivory. Physiologically, polar bears are extremely
23 well adapted to feed on a diet high in fat; store fat for later future energy needs; and enter
24 and sustain periods of reduced metabolism whenever food is in short supply (Derocher et
25 al. 1990; Atkinson and Ramsay 1995). Feeding success is strongly related to ice
26 conditions; when stable ice is over productive shelf waters, polar bears can feed
27 throughout the year on their primary prey, ringed seals (Stirling and McEwan 1975;
28 Stirling and Smith 1975; Stirling and Archibald 1977; Amstrup and DeMaster 1988;
29 Amstrup et al. 2000). Less frequently, they feed on other marine mammals (Smith 1980,
30 1985; Calvert and Stirling 1990) and even more rarely on terrestrial foods (Lunn and
31 Stirling 1985; Derocher et al. 1993). Polar bears exhibit the behavioral plasticity typical
32 of top-level predators, and they are adept at capturing seals from the ice (Stirling 1974;
33 Stirling and Derocher 1993).
34
35 Today, an estimated 20,000 to 25,000 polar bears live in 19 apparently discrete
36 populations distributed around the circumpolar Arctic (IUCN Polar Bear Specialists
37 Group 2005). Their overall distribution largely matches that of ringed seals, which
38 inhabit all seasonally ice-covered seas in the Northern Hemisphere (Scheffer 1958; King
39 1983), an area extending to approximately 15,000,000 km^2. Polar bears are not regularly
40 found, however, in some of the marginal seas (e.g., the Okhotsk Sea) inhabited by ringed
41 seals. The broad distribution of their seal prey is reflected in the home ranges of polar
42 bears that, averaging over 125,000 km^2, are more than 200 times larger than the averages
43 for terrestrial carnivores of similar size (Durner and Amstrup 1995; Ferguson et al. 1999).
44 Most polar bear populations expand and contract their range seasonally with the
45 distribution of sea ice, and they spend most of year on the ice (Stirling and Smith 1975;

Garner et al. 1994). Most populations, however, retain their ancestral tie to the terrestrial environment for denning, although denning on the sea ice is common among the bears of the Beaufort and Chukchi seas (Harrington 1968; Stirling and Andriashek 1992; Amstrup and Durner 1994; Messeir et al. 1994; Durner et al. 2003). Dens on land and on ice are excavated in snow drifts, the stability and predictability of which are essential to cub survival (Blix and Lentfer 1979; Ramsay and Stirling 1988, 1990; Clarkson and Irish 1991).

The rapid rates of warming in the Arctic observed in recent decades and projected for at least the next century are dramatically reducing the snow and ice covers that provide denning and foraging habitat for polar bears (Roots 1989; Overpeck et al. 1997; Serreze et al. 2000; Stroeve et al. 2007). These changes to their environment will exert new, strong selection pressures on polar bears. Adaptive traits reflect selection by past environments, and the time needed to adapt to new environments depends on genetic diversity in populations, the intensity of selection, and the pace of change. Genetic diversity among polar bears is evident in the 19 putative populations, suggesting some scope for adaptation within the species as a whole even if some populations will be at greater risk than others. On the other hand, the nature of the environmental change affecting critical features of polar bears' breeding and foraging habitats, and the rapid pace of change relative to the bears' long generation time (circa 15 years) do not favor successful adaptation.

The most obvious change to breeding habitats is the reduction in the snow cover on which successful denning depends (Blix and Lenter 1979; Amstrup and Gardner 1994; Messier et al. 1994; Durner et al. 2003). Female polar bears hibernate for four to five months per year in snow dens in which they give birth to cubs, typically twins, each weighing just over 0.5 kg (Blix and Lentfer 1979). The small cubs depend on snow cover to maintain thermal neutrality. Whether it remains within the genetic scope of polar bears to revert to the ancestral habit of rearing in earthen dens is unknown.

Changes in the foraging habitat that will entail new selection pressures include seasonal mismatches between the energetic demands of reproduction and prey availability; changes in prey abundance; changes in access to prey; and changes in community structure.

Emergence of female and young polar bears from dens in the spring coincides with the ringed seal's birthing season, and the newly emerged bears depend on catching and consuming young seals to recover from months of fasting (Stirling and Øritsland 1995). That coincidence may be disrupted by changes in timing and duration of snow and ice cover. Such mismatches between reproductive cycles and food availability are increasingly recognized as a means by which animal populations are impacted by climate change (Stenseth and Mysterud 2002; Stenseth et al. 2002; Walther et al. 2002).

Recognized as the most abundant of northern seals, ringed seal populations also may decline as the sea ice habitat changes (Stirling and Derocher 1993; Kelly 2001). Like polar bears, ringed seals depend on snow caves for rearing their young, and increasingly

early snow melts have led to high rates of seal mortality due to hypothermia and predation (Lydersen and Smith 1989; Kelly 2001; Stirling and Smith 2004). Walruses (*Odobenus* rosmarus) and bearded seals (*Erignathus barbatus*) can also be important prey of polar bears, and the ecology of these pinnipeds is also tightly coupled to the sea ice environment, such that their populations are vulnerable to reductions in ice cover (Tynan and DeMaster 1997; Kelly 2001; Grebmeier et al. 2006).

The polar bear's ability to capture seals depends on the presence of ice. In that habitat, bears take advantage of the fact that seals must surface to breathe in limited openings in the ice cover. In the open ocean, however, bears lack a hunting platform, seals are not restricted in where they can surface, and successful predation is exceedingly rare (Furnell and Oolooyuk 1980). Only in ice-covered waters are bears regularly successful at hunting seals. When restricted to shorelines, bears feed little if at all, and terrestrial foods are thought to be of little significance to polar bears (Lunn and Stirling 1985; Ramsay and Hobson 1991). Predation on reindeer observed in Svalbard, however, indicates that polar bears have some capacity to switch to alternate prey (Derocher et al. 2000).

Seal and other prey populations also will be impacted by fundamental changes in the fate of primary production. For example, in the Bering and Chukchi seas, the reduction in sea ice cover alters the physical oceanography in ways that diminish carbon flow to the benthos, and increase carbon recycling in pelagic communities (Grebmeier et al. 2006). The resultant shift in community structure will include higher trophic levels. The exact composition of future communities is not known, nor is it known how effectively polar bears might exploit those communities.

During previous climate warmings, polar bears apparently survived in some unknown refuges. Whether they can withstand the more-extreme warming ahead is doubtful (Stirling and Derocher 1993; Lunn and Stirling 2001). As snow and ice covers decline, polar bears may respond adaptively to the new selection pressures or they may become extinct. Extinction could result from mortality outpacing production, or from re-absorption into the brown bear genome. Crosses between polar bears and brown bears produce fertile offspring (a hybrid was recently document in the wild), and extinction through hybridization has been documented in other mammals (Rhymer and Simberloff 1996).

5.7 Ecosystem Services and Expectations for Future Change

The Millennium Ecosystem Assessment (MA) (2006) is the most comprehensive scientific review of the status, trends, conditions, and potential futures for ecosystem services. It was international in coverage, although individual sections did focus on regions, ecosystem types, and particular ecosystem services. The MA categorized services as supporting, provisioning, regulating, and cultural (Figure 5.1). Some of these services are already traded in markets, e.g. provision of food, wood, and fiber from both managed and unmanaged ecosystems, or the cultural services of providing recreational activities that generate substantial revenue both within the United States and

1 globally. Other services, in particular many cultural services, regulating services, and
2 supporting services are not priced, and therefore not traded in markets. A few, like
3 provision of fresh water or carbon sequestration potential, are mostly not traded in
4 markets, but could be, and especially for carbon, there are many developing markets.

ECOSYSTEM SERVICES

Provisioning
- FOOD
- FRESHWATER
- WOOD AND FIBER
- FUEL
- ...

Supporting
- NUTRIENT CYCLING
- SOIL FORMATION
- PRIMARY PRODUCTION
- ...

Regulating
- CLIMATE REGULATION
- FLOOD REGULATION
- DISEASE REGULATION
- WATER PURIFICATION
- ...

Cultural
- AESTHETIC
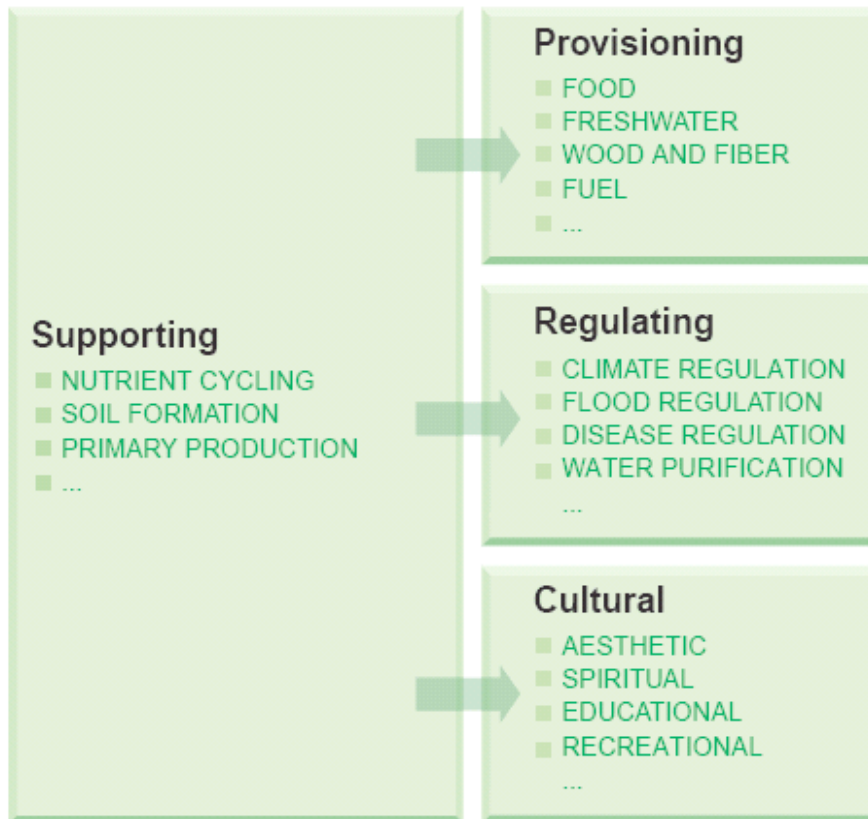- SPIRITUAL
- EDUCATIONAL
- RECREATIONAL
- ...

Figure 5.1

32 Biological diversity is recognized as providing an underpinning for all these services in a
33 fundamental way. A major finding of the MA from a global perspective was that out of
34 24 different ecosystems services that were analyzed, 16 were being used in ultimately
35 unsustainable ways. While this finding was not specific to U.S. ecosystems, it does set a
36 context within which the changes that have been documented as a consequence of
37 changes in the physical climate need to be considered.

39 A subsequent question is whether any such changes in services can be reasonably
40 attributed to climate change. The MA evaluated the relative magnitudes and importance
41 of a number of different direct drivers (Nelson et al. 2006) for changes in ecosystems,
42 and whether the importance of those drivers was likely to increase, decrease, or stay
43 about the same over the next several decades. The conclusion was that although climate
44 change was not currently the most important driver of change in many ecosystems, it was

1   one of the only drivers whose importance was likely to continue to increase in all
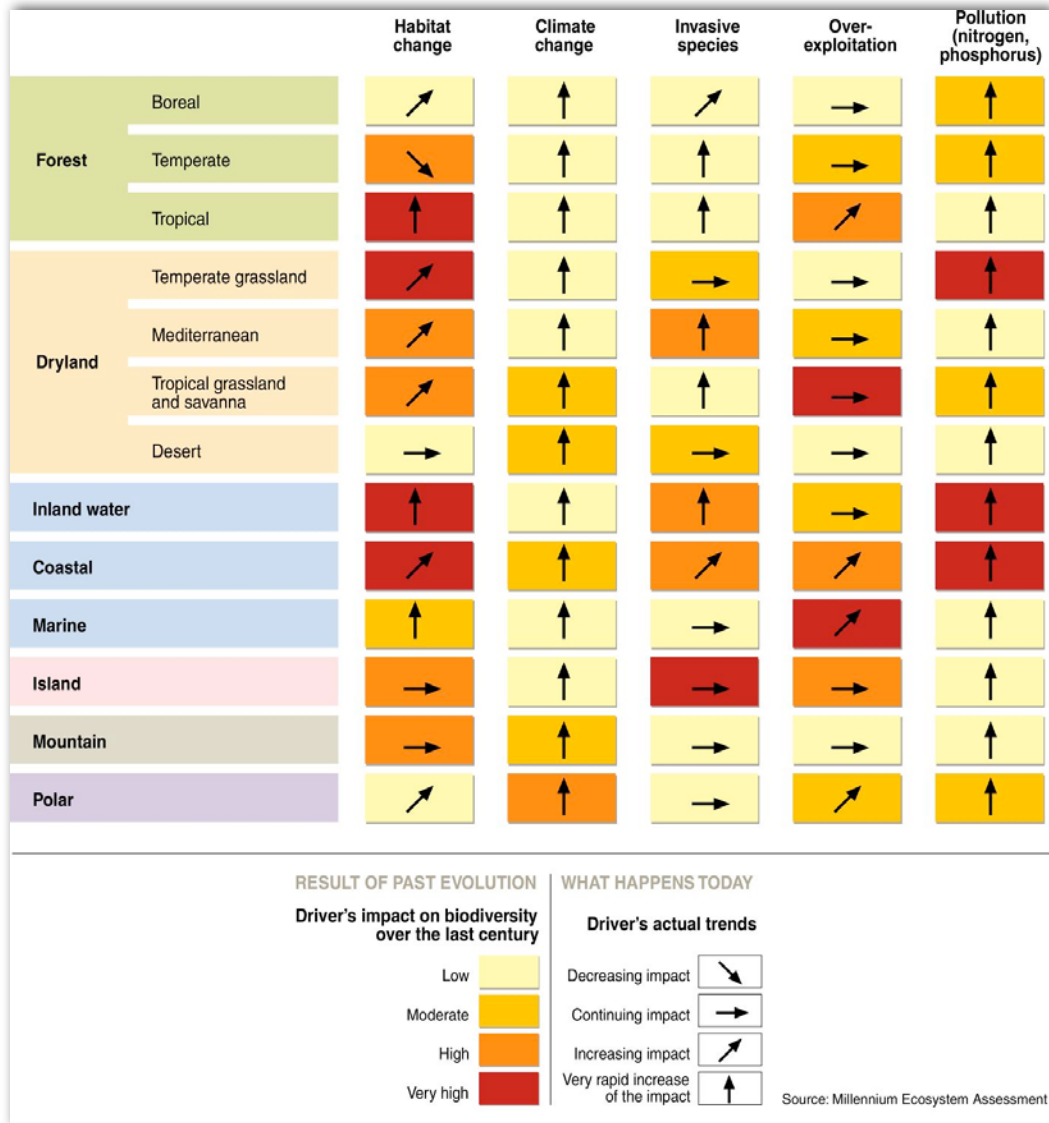2   ecosystems over the next several decades (Figure 5.2).

Figure 5.2

5.8 Adequacy of observing systems

One of the challenges for understanding changes in biological diversity related to
variability and change in the physical climate system is the adequacy of the variety of
monitoring programs that exist for documenting those changes.

1   It is useful to think about such programs as falling into three general categories. The first
2   is the collection of operational monitoring systems that are sponsored by federal
3   agencies, conservation groups, state agencies, or groups of private citizens that are
4   focused on particular taxa (e.g. the Breeding Bird Survey), or particular ecosystems (e.g.
5   Coral Reef Watch). These tend to have been established for very particular purposes, e.g.
6   tracking the abundance of migratory songbirds, or the status and abundance of game
7   populations within individual states, or the status and abundance of threatened and
8   endangered species.
9
10 A second category of monitoring programs are those in which initial justification has
11 been to investigate particular research problems, whether primarily oriented around
12 biodiversity or not. So, for example, the existing LTER sites are important for monitoring
13 and understanding trends in biodiversity in representative biomes in the United States,
14 although their original justification was much more oriented around understanding
15 ecosystem functioning. The yet-to-be established NEON network would also fall into this
16 category, although the published design for site locations samples both climate variability
17 and ecological variability within the United States in a much more systematic way than
18 ever before for a long-term research network, so there are likely to be very powerful
19 results that can potentially come from network-wide analyses.
20
21 The table below lists a large number of operational and research monitoring networks
22 that fall into these first two categories.
23
24 A third category of monitoring systems are those that offer the extensive spatial and
25 variable temporal resolution of remotely sensed information from Earth-orbiting
26 satellites. These are not always thought of as being part of the nation's system for
27 monitoring biological diversity, but in fact, they are an essential component of it.
28 Remotely sensed data are the primary source of information on a national scale for
29 documenting land-cover and land-cover change across the United States, for example,
30 and thus they are essential for tracking changes in perhaps the biggest single driver of
31 changes in biodiversity – i.e. changes in habitat. Over the 1990s and 2000s, the
32 remarkable profusion of Earth observation satellites has provided global coverage of
33 many critical environmental parameters, from variability and trends in the length of
34 growing season, to NPP monitoring, to the occurrence of fires, to the collection of global
35 imagery on 30-meter spatial resolution for more than a decade. Observational needs for
36 biodiversity monitoring and research are recently reviewed by the International Global
37 Observations of Land Panel, in a special report from a conference (IGOL 2006).
38
39 However, in recent years, the U.S. contribution to such measurements has waned, and
40 new systems have been slow to be developed by NASA and NOAA. The National
41 Research Council has recently released the first-ever Decadal Survey for Earth Science
42 and Observations, which makes a comprehensive set of recommendations for future
43 measurements and missions, which would simultaneously enhance scientific progress,
44 preserve essential data sets, and benefit a wide variety of potential applications.
45

1   Are these existing monitoring systems adequate for monitoring changes in biodiversity
2   associated with climate variability and change? Although there are lists of specifications
3   for monitoring systems that would be relevant and important for this purpose (e.g. IGOL
4   2007), there is at present no analysis in the literature that has addressed this question
5   directly. So, for the moment, there is no viable alternative to using the existing systems
6   for that purpose, even if it means that the scientific community is attempting to use them
7   for a purpose other than what they were originally designed for. There has obviously
8   been some considerable success so far in doing so, but there is limited confidence that the
9   existing systems provide a true early warning system.
10

11   5.8.1 Table: Existing monitoring systems

12   *5.8.1.1 Bird Monitoring in North America*

13
14   Canadian Bird Checklist Program (http://www.oiseauxqc.org/feuillets/cbcp_can.html)
15   Project FeederWatch (http://www.birds.cornell.edu/PFW/)
16   Breeding Bird Survey (http://www.pwrc.usgs.gov/bbs/)
17   Breeding Bird Survey Summary and Analysis (http://www.mbr-
18   pwrc.usgs.gov/bbs/bbs.html)
19   Christmas Bird Count (http://www.audubon.org/bird/cbc/index.html)
20   Point Count Database (http://www.pwrc.usgs.gov/point/)
21   Breeding Bird Census (http://www.pwrc.usgs.gov/birds/bbc.html)
22   Bird Banding Laboratory (http://www.pwrc.usgs.gov/bbl/)
23   Monitoring Avian Productivity and Survivorship (http://www.birdpop.org/maps.htm)
24   Migration Monitoring
25   Marsh Bird Monitoring (http://www.bsc-eoc.org/)
26   *Night Bird Monitoring*
27   *Winter Bird Survey*
28   Urban Birds (Birdscape Project) (http://www.pwrc.usgs.gov/birdscap/scapein.html)
29   Waterbird Monitoring Partnership (http://www.waterbirdconservation.org/)
30   International Shorebird Survey (http://www.pwrc.usgs.gov/iss/iss.html)
31   Waterfowl and Gamebird Surveys
32   (http://www.fws.gov/migratorybirds/statsurv/mntrtbl.html#tbl)
33   Hawk Migration Monitoring (http://www.hawkmountain.org/default.shtml)
34   Forest Bird Monitoring (http://www.cwf-
35   fcf.org/pages/wildresources/surveys/survey18.htm)
36   Project NestWatch Canada (http://www.bsc-eoc.org/national/nestwatch.html)
37   BioBlitz (http://www.pwrc.usgs.gov/blitz.html)

38   *5.8.1.2 Amphibian Monitoring*

39
40   North American Amphibian Monitoring Program (http://www.pwrc.usgs.gov/naamp/)
41   Northeast Amphibian Monitoring Program (http://www.pwrc.usgs.gov/nearmi/)

*5.8.1.3 **Mammal Monitoring in North America***

*5.8.1.4 **Butterfly Monitoring in North America***

*5.8.1.5 **General Biodiversity Monitoring:***

*5.8.1.6 **Long-Term Ecological Research (LTER) sites***

The LTER Network is a collaborative effort involving more than 1800 scientists and students investigating ecological processes over long temporal and broad spatial scales. http://www.lternet.edu/

National Ecological Observatory Network (NEON)
http://www.neoninc.org/archive/2005/01/subscribe_to_th.html

National Park Service Inventory and Monitoring Program
Baseline inventories of basic biological and geophysical natural resources with long-term monitoring programs efficiently and effectively monitor ecosystem status and trends over time at various spatial scales.
http://www1.nature.nps.gov/protectingrestoring/IM/inventoryandmonitoring.htm

NatureServe
Documents the condition and distribution of species and ecosystems, with an emphasis on those of greatest conservation concern.
http://www.natureserve.org/projects/united_states.jsp

Smithsonian Institution's Monitoring and Assessment of Biodiversity Program (MAB) works internationally with governments, industries, academia, nongovernmental organizations, local communities, and others to assess and monitor the biodiversity in the tropical and temperate forests of Latin America, the Caribbean, North America, Africa, and Asia. http://nationalzoo.si.edu/ConservationAndScience/MAB/about/

Strategic Plan for North American Cooperation in the Conservation of Biodiversity seeks to enhance collaboration among Canada, Mexico, and the United States in furthering the conservation and sustainable use of biodiversity, in particular transboundary and migratory species.

United Nation Environment Programme World Conservation Monitoring Centre (IUCN WCMC) UNEP-WCMC, in collaboration with the UNESCO World Heritage Centre (WHC) and IUCN, has prepared a review of the World Heritage network in relation to global biogeography, biodiversity and habitats. The assessment is a contribution to the World Heritage Global Strategy. The Global Strategy adopted by the World Heritage Committee aims to achieve a balanced, representative and credible World Heritage List that reflects the world's diverse heritage
http://www.unep-wcmc.org/protected_areas/world_heritage/wh_review.htm

United States Geological Survey

Natural Resources Canada and the U.S. Geological Survey have a high-tech satellite mapping initiative to better monitor changes in the combined land cover of the two nations.

NOAA Coral Reef Watch

5.9 Major Findings and Conclusions

In this section, we list the major findings from each section of the chapter, by topic heading. We then draw some general conclusions about the observed and potential impacts of climate change on biological diversity, the relationships to ecosystem sevices, and the adequacy of existing monitoring systems to document continuing chang**e.**

5.9.1 Growing Season and Phenology

There is evidence indicating a significant lengthening of the growing season and higher NPP in the higher latitudes of North America, where temperature increases are relatively high.

Over the last 19 years, global satellite data indicates an earlier onset of spring across the temperate latitudes by 10 to 14 days (Myeni 2001; Lucht 2002), an increase in summer photosynthetic activity (NDVI satellite estimates, (Myeni 2001)), and an increase in the amplitude of annual CO_2 cycle (Keeling, 1996), all supported by climatological and field observations.

Forest productivity, in contrast, generally limited by low temperature and short growing seasons in the higher latitudes and elevations, has been slowly increasing at less than one percent per decade (Boisvenue 2006; Joos 2002; McKenzie 2001; Caspersen 2000).

The exception to this pattern is in forested regions that are subject to drought from climate warming, where growth rates have decreased since 1895 (McKenzie 2001. Recently, widespread mortality over 12,000 km^2 of lower elevational forest in the southwest U.S. demonstrate the impacts of increased temperature and the associated multiyear drought (Breshears 2005) even as productivity at treeline had increased previously (Swetnam, 1998).

Disturbances created from the interaction of drought, pests, diseases, and fire are projected to have increasing impacts on forests and their future distributions (IPPC FER SPM 2007). These changes in forests and other ecosystems will cascade through trophic webs, impacting other species.

5.9.2 Biogeographical and phenological shifts

Evidence from two meta-analyses (143 studies, (Root 2003); 1,700 species, (Parmesan 2003)) and a synthesis (866 studies, (Parmesan 2006)) on species from a broad array of taxa suggest that there is a significant impact of recent climatic warming in the form of long-term, large-scale alteration of animal and plant populations.

1
2 Movement of species in regions of North America in response to climate warming is
3 expected to result in shifts of species ranges poleward and upward, along elevational
4 gradients (Parmesan 2006).
5
6 In an analysis of 866 peer-reviewed papers exploring the ecological consequences of
7 climate change, nearly 60 percent of the 1,598 species studied exhibited shifts in their
8 distributions and/or phenologies over the a 20 and 140 year time frame (Parmesan 2003).
9
10 Analyses of field-based phenological responses have reported shifts as great as 5.1 days
11 per decade (Root 2003), with an average of 2.3 days per decade across all species
12 (Parmesan 2003).
13
14 *Migratory Birds*
15
16 A climate change signature is apparent in the advancement of spring migration phenology
17 (Root 2003), but the indirect effects may be more important than the direct effects of
18 climate in determining the impact on species persistence and diversity.
19
20 *Butterflies*
21
22 The migration of butterflies in the spring is highly correlated with spring temperatures,
23 and with early springs; researchers have documented many instances of earlier arrivals
24 (26 of 35 species in the United Kingdom, (Roy 2000); 17 of 17 species in Spain,
25 (Stefanescu 2004); 16 0f 23 species in central California, and (Forister 2003).
26
27 Butterflies are also exhibiting distributional and/or range shifts in response to warming.
28 Across all studies included in her synthesis, Parmesan (2006) found 30-75 percent of
29 species had expanded northward, less than 20 percent had contracted southward, and the
30 remainder were stable (Parmesan 2006).
31

32 **5.9.3 Coastal and Near Shore Systems**
33
34 In the tropics there have been increasing coral bleaching and disease events and
35 increasing storm intensity. In temperate regions there are demonstrated range shifts and
36 possible alterations of ocean currents and upwelling sites. In the Arctic, there have been
37 dramatic reductions in sea ice extent and thickness, as well as related coastal erosion.
38 Marine species were the first to be listed due to the effects of climate change.
39

40 **5.9.4 Corals**
41
42 Corals and tropical regions where they live are experiencing increasing water
43 temperatures, increasing storm intensity (Emmuel 2005), and a reduction in pH (Ravens
44 et al. 2005), all while experiencing a host of other on-going challenges from

1 development/tourism, fishing and pollution.
2
3 The major threats that motivated the listings of Elkhorn (*Acropora palmata*) and
4 Staghorn (*A. cervicornis*) corals were disease, elevated sea surface temperatures and
5 hurricanes – all of which relate to climate change.
6

5.9.5 Coastal Lands

8

9 Projections for sea level rise by 2100 vary from 0.18 to 0.59 meters (±0.1-0.2) (IPCC
10 2007), to 0.5 to 1.4 m (Rahmstorf 2007). It has been estimated that a one-meter increase
11 in sea level would lead to the loss of 65 percent of the coastal marshlands and swamps in
12 the contiguous United States (Park et al. 1989). In addition to overt loss of land, there
13 will also be shifts in "quality" of habitat in these regions. Prior to being inundated,
14 coastal watershed will become more saline due to saltwater intrusion into both surface
15 and groundwater.
16
17 Climate change will also lead increasing coastal erosion through several processes such
18 as increasing coastal storm intensity, shifts to fewer more intense storm events in some
19 regions, and loss of sea ice cover during traditional storm seasons. While these issues
20 have been well addressed in terms of human infrastructure and settlement vulnerability to
21 climate change, they have been less well explored in terms of biodiversity.
22

5.9.6 Arctic

24

25 Changes in the Arctic are resulting in substantial shifts in habitat, especially for sea ice-
26 dependent species, where it is literally melting away. The sea ice, which provides habitat
27 both below and above the ocean, has been in retreat for at least 30 years (Stroeve et al.
28 2005; Rothrock et al. 2003). It is estimated that a summer-ice-free Arctic Ocean is likely
29 by the end of the century (Overpeck et al. 2005), with some models suggesting it could be
30 as soon as 2040 (Holland et al. 2006).
31
32 Ice loss to date is already causing measurable changes in polar bear and ringed seal
33 populations and fitness (Derocher et al. 2004; Ferguson et al. 2005; Stirling et al. 1999).
34 There are also shifts in species ranges in the Arctic, both on land and in the water, and
35 changes in phenology.
36

5.9.7 Pests and Pathogens

38

39 Evidence is beginning to accumulate that links the spread of pathogens to a warming
40 climate. For example, the chytrid fungus (*Batrachochytrium dendrobatidis*) is a pathogen
41 that is rapidly spreading world-wide, and decimating amphibian populations. A recent
42 study by Pounds and colleagues (2006) showed that widespread amphibian extinction in
43 the mountains of Costa Rica is positively linked to global climate change.

To date, geographic range expansion of pathogens related to warming temperatures have been the most easily detected (Harvell et al. 2002), perhaps most readily for arthropod-borne infectious disease (Daszak et al.). However, a recent literature review found additional evidence gathered through field and laboratory studies that support hypotheses that latitudinal shifts of vectors and diseases are occurring under warming temperatures.

5.9.8 Invasive Plants

Projected increases in CO_2 are expected to stimulate the growth of most plants species, and some invasive plants are expected to respond with greater growth rates than non-invasive plants. Some invasive plants may have higher growth rates, and greater maximal photosynthetic rates relative to native plants under increased CO_2, but definitive evidence of a general benefit of CO_2 enrichment to invasive plants over natives has not emerged (Dukes and Mooney 1999).

Nonetheless, in general, invasive plants may better tolerate a wider range of environmental conditions, and may be more successful in a warming world because they can migrate and establish in new sites more rapidly than native plants, and they are not usually limited by pollinators or seed dispersers (Vila et al. *In Press*).

Finally, it is critical to recognize that other elements of climate change (e.g., nitrogen deposition, land conversion) will play a significant role in the success of invasive plants in the future, either alone or under elevated CO_2 (Vila et. al. *In Press*).

5.9.9 Marine Fisheries

Large basin-scale atmospheric pressure systems that drive basin-scale winds can suddenly shift their location and intensity at decadal time scales, with dramatic impacts on winds and ocean circulation patterns. Perhaps the greatest discovery of the past 10 years is that these shifts have dramatic impacts on marine ecosystems.

Examples include increased flow of oceanic water into the English Channel and North Sea, resulting in a northward shift in the distribution of zooplankton such that the zooplankton community became dominated by warm water species (Beaugrand 2004), with concomitant changes in fish communities from one dominated by whiting (hake) to one dominated by sprat (similar to a herring).

Similar (and drastic) ecosystem changes are known for the Baltic Sea (Kenny and Mollman 2006), where dramatic changes in both zooplankton and fish communities were observed. Cod were replaced by sprat and dominance in zooplankton switched from lipid-rich (and high bioenergetic content) species to lipid-poor species.

Linkages between the NAO, zooplankton, and fisheries have also been described for the Northwest Atlantic, waters off eastern Canada and the United States: Pershing and Green (2007) report a decrease in salinity, and an increase in biomass of small copepods (zooplankton). They suggest that the recovery of the codfish populations, which collapsed in the early 1990s (presumably as a result of overfishing), may continue to be difficult due to negative changes in food chain structure of their forage base, the zooplankton.

5.9.10 Particular Sensitive Systems

Plant and animal communities are also affected as glaciers recede, exposing new terrain for colonization in an ongoing process of succession. One group of organisms whose reproductive phenology is closely tied to snowmelt is amphibians, for which this environmental cue is apparently more important than temperature.

Hibernating and migratory species that reproduce at high altitudes during the summer are also being affected by ongoing environmental changes. For example, marmots are emerging a few weeks earlier than they used to in the Colorado Rocky Mountains, and robins are arriving from wintering grounds weeks earlier in the same habitats. Species such as deer, bighorn sheep, and elk, which move to lower altitudes for the winter, may also be affected by changing temporal patterns of snowpack formation and disappearance.

The annual disappearance of snowpack is the environmental cue that marks the beginning of the growing season in most montane environments. Thus it is not surprising that flowering phenology has been advancing in these habitats, as well as others at lower altitudes, mirroring what is going on at higher latitudes.

There is a very strong correlation between the timing of snowmelt, which integrates snowpack depth and spring air temperatures, and the beginning of flowering by wildflowers in the Colorado Rocky Mountains.

For some wildflowers there is also a strong correlation between the depth of snowpack during the previous winter and the abundance of flowers produced.

An unexpected consequence of earlier snowmelt in the Rocky Mountains has been the increased frequency of frost damage to montane plants, including loss of new growth on conifer trees, of fruits on some plants such as *Erythronium grandiflorum* (glacier lilies), and of flower buds of other wildflowers (e.g., *Delphinium* spp., *Helianthella quinquenervis*, etc.). Although most of these species are long-lived perennials, as the number of years in which frost damage has negative consequences on recruitment increases, significant demographic consequences may result.

5.9.11 Polar Bears

Today, an estimated 20,000 to 25,000 polar bears live in 19, apparently discrete
populations distributed around the circumpolar Arctic (IUCN Polar Bear Specialists
Group 2005). Their overall distribution largely matches that of ringed seals, which
inhabit all seasonally ice-covered seas in the northern hemisphere (Scheffer 1958; King
1983), an area extending to approximately 15,000,000 km^2.

Most polar bear populations expand and contract their range seasonally with the
distribution of sea ice, and they spend most of the year on the ice (Stirling and Smith
1975; Garner et al. 1994).

The rapid rates of warming in the Arctic observed in recent decades and projected for at
least the next century are causing dramatic reduction of snow and ice cover, which
provide denning and foraging habitat for polar bears (Roots 1989; Overpeck et al. 1997;
Serreze et al. 2000; Stroeve et al. 2007).

During previous climate warmings, polar bears apparently survived in some unknown
refuges. Whether they can withstand the continued loss of sea ice from the more extreme
warming ahead is doubtful (Stirling and Derocher 1993; Lunn and Stirling 2001).

Conclusions

Terrestrial systems are already being demonstrably impacted by climate change. There
are observable impacts of climate change on terrestrial ecosystems in North America
including changes in the timing of growing season and its length, phenology, primary
production, and species distributions and diversity. Some important effects on
components of biological diversity have already been observed and are increasingly well-
documented over the past several decades. This statement is true both for ecosystems in
the United States, and also, as the IPCC (2007) states, for ecosystems and biological
resources around the world.

There are a family of other impacts and changes in biodiversity that are theoretically
possible, and even probable (e.g. mismatches in phenologies between pollinators and
flowering plants), but for which we do not yet have a substantial observational database.
However, we cannot conclude that the lack of a complete observational database in these
cases is evidence that they are not occurring – it is just as likely that it is simply a matter
of insufficient numbers, or lengths of observations.

It is difficult to pinpoint changes in ecosystem services specifically related to changes in
biological diversity in the United States. The MA (2005) is the most recent, and most
comprehensive scientific assessment of the state of ecosystem services around the world,
the drivers of changes in both ecosystems and services, the inherent tradeoffs among
different types of ecosystem services, and what the prospects are for sustainable use of
ecological resources. The MA concludes that climate change is likely to increase in

importance as a driver for changes in biodiversity over the next several decades, although for most ecosystems it is not currently the largest driver of change. But a specific assessment of changes in ecosystem services for the Unitd States as a consequence of changes in climate or other drivers of change has not been done.

We can think of the monitoring systems that have been used to evaluate the relationship between changes in the physical climate system and biological diversity as having three components. There is a plethora of species-specific or ecosystem-specific monitoring systems, variously sponsored by U.S. federal agencies, state agencies, conservation organizations, and other private organizations. However, in very few cases were these monitoring systems established with climate variability, and climate change in mind. Augmenting the monitoring systems that make routine measurements are a set of more specific research activities that have been specifically designed to create time-series of population data, and associated climatic and other environmental data. These systems, however, tend to lack the institutional stability to create, manage, and maintain long time-series of observations.

The third components are spatially extensive observations derived from remotely sensed data. These are primarily focus on land-cover, and thus are a good indicator of the major, single drivers of changes in biodiversity patterns, or on estimating ecosystem functioning – such as producing estimates of NPP and changes in the growing season – and thus reflect functional changes more easily than structural changes. However, similarly to the in situ monitoring networks, the space-based observations' future is not assured. The NRC (2007) recently released a major survey of data and mission needs for the Earth sciences to address this issue, so we will not pursue it further here.