III. Assessing the Components of Vulnerability

This chapter provides a more detailed treatment of how to apply the sensitivity, exposure, and adaptive capacity framework presented in the previous chapter for conducting a vulnerability assessment. Depending on the objective of the analysis, whether it focuses on a single species, specific habitat, ecosystem, or geographic place—different components will be more or less useful. Some elements will be useful for assessing the vulnerability of a wide range of targets (species, habitats, or ecosystems). Below, we first describe these "universal" elements, that is, aspects that are relevant to most any vulnerability analysis. We then provide descriptions of some of the elements that are better suited to assessing the vulnerability of particular targets.

Many of the sensitivity elements that apply across biological levels are associated with physical systems and processes.

Assessing Sensitivity

Universal Elements of Sensitivity

Many of the critical sensitivity elements that apply across biological levels—that is, to species, habitats, and ecosystems—are associated with the earth's physical systems and processes such as hydrology, fire, and wind. Although there are other sensitivity factors that affect all three levels of ecological organization, they tend to do so through their effects on individuals or species. Thus, most sensitivity factors are described in the species subsection, below.

Hydrology

Both terrestrial and aquatic species, habitats, and ecosystems can be sensitive to changes in hydrology. For example, salmon spawning and migration are sensitive to the timing and the volume of stream flows; the composition and structure of forest stands are sensitive to the availability of ground water; and dissolved oxygen levels, water temperatures, decomposition rates, and other wetland attributes are sensitive to the amount of water flowing into and out of the wetland. Other species are sensitive to reductions in snowpack, such as the American wolverine, which requires persistent spring snow cover for its natal dens (Copeland et al. 2010; Aubry et al. 2007).

Fire

Individual species as well as habitats and ecosystems can be sensitive to changes in the frequency, severity, and extent of fires. For example, plant species that depend

Lead authors: Josh Lawler, Carolyn Enquist, and Evan Girvetz.

on fire for germination and conversely species that are intolerant of intense fires are sensitive (albeit in different ways) to changes in fire regimes. The degree to which a plant community type is sensitive to changes in fire regimes will depend not only on the individual sensitivities of its component species, but also on any synergistic effects that particular combination of species and their spatial arrangement has on fire behavior (e.g., the structure of the vegetation, the ground-level accumulation of fine fuels, and the invasion of habitat by plant species, such as cheatgrass or buffelgrass, that can alter a system's fire regime) (Young and Blank 1995). Similarly, an ecosystem's sensitivity to fire will be affected by the sensitivities of its component species and habitats, but also by topography, hydrology, and potentially by the spatial arrangement of habitat types and the sensitivities of neighboring ecosystems.

Wind

Sensitivities to changes in wind and storm events also may apply across multiple biological levels. For example, individual tree species will be more or less sensitive to wind based on their physiologies. Habitats and ecosystems will be more or less sensitive depending on their component species but also the arrangement and composition of those species and potential interactions between wind events, insect outbreaks, and fire. Longleaf pine trees, for example, are considered to be less sensitive to wind storms than are loblolly pine and slash pine (McNulty 2002). When encountering hurricane-force winds, longleaf pine trees are more likely than these other species to have minimal damage or be blown over, rather than snapping midstem or becoming completely uprooted, as their large taproot and widespread lateral root system provide them with greater stability. For another example, wind can transport dust from lower-elevation deserts to higher-elevation snowfields, increasing the rate of snowmelt (Steltzer et al. 2009). This can, in turn, lead to early germination in many plant species, leaving them susceptible to frost damage and, in some cases, mortality (Inouye 2008).

Species-Level Sensitivities

Physiological Factors

Species-level sensitivities often are characterized by physiological factors such as changes in temperature, moisture, CO_2 concentrations, pH, or salinity. These physiological sensitivities can be thought of as direct sensitivities to climate change. Examples of sensitivities to changes in temperature are cold-water fish species with maximum temperature tolerances (e.g., bull trout), turtles with temperature-dependent sex ratios, and trees with frost tolerances or required growing-season lengths (Dunham et al. 2003; Janzen 1994; Luedeling et al. 2009). Examples of direct physiological sensitivities to changes in moisture include germination requirements in plants, moisture requirements for some amphibians, nest microclimate requirements for incubation or nestling survival in birds, and snowpack-insulation effects on high-elevation plants and animals (e.g., the American pika, which exhibits high temperature sensitivity during the summer months) (Fay et al. 2009; Blaustein et al. 2010; Rauter et al. 2002; Smith and Weston 1990). Increases in atmospheric CO_2 concentrations can increase water use efficiency in plants and therefore increase growth through "CO_2 fertilization" (Belote et al. 2003). Increasing CO_2 concentrations are also affecting the pH of marine and, in some cases, freshwater systems. For example, many corals and other species with calcareous exoskeletons or shells will be sensitive to changes in pH (Kuffner and Tihansky 2008).

Dependence on Sensitive Habitats

In many cases, individual species' sensitivity is likely to be influenced by the sensitivity of its habitat to climate change (McCarty 2001). For example, species that breed in vernal pools, ephemeral wetlands, intermittent streams, and species that live in alpine environments or low-lying coastal zones are all likely to be highly susceptible to climate impacts such as rising temperature regimes; winter precipitation arriving more frequently as rain than snow; shifts in the timing of snowmelt, runoff, and peak flows in streams; and sea-level rise. In some cases, it may suffice to highlight species that are linked to highly sensitive habitats such as those listed above. In other cases, one might want to conduct a detailed habitat sensitivity assessment (based on some of the factors listed below in the section on habitat-specific sensitivities).

Ecological Linkages

Species' sensitivities also likely depend on the effects of climate change on predators, competitors, prey, forage, host plants, diseases, parasites, and other groups of species that affect the focal species (Parmesan 2006). For example, there may be changes in the occurrence or abundance of predators or prey that subsequently affect the focal species (Visser and Both 2005). There may also be changes in the interspecific relationships themselves. CO_2-driven increases in water use efficiency have the potential to change the competitive relationship among species. Likewise, an increase in temperature could increase the feeding efficiency of a warm-water fish species, allowing it to better compete with a cool-water species.

Other key examples of changes in ecological linkages might include changes in the community of invasive species (e.g., new invaders), changes in the frequency or intensity of pest outbreaks, and changes in the prevalence, spread, and susceptibility to disease. For example, increases in temperature have allowed mountain pine beetles to complete their life cycles within a single year at higher elevations, exposing previously isolated whitebark pine to beetle outbreaks (Logan et al. 2003; Logan and Powell 2001). Similarly, changes in climate have been implicated in the range shift of the disease-causing chytrid fungus, potentially affecting previously isolated amphibian populations and species (Pounds et al. 2006; Bosch et al. 2007).

Phenological Changes

Phenology refers to recurring plant and animal life-cycle stages, such as leafing and flowering of plants, maturation of agricultural crops, emergence of insects, and migration of birds. Many of these events are sensitive to climatic variation and change (Parmesan and Yohe 2003), and when the timing and sequence of these events are altered, loss of species and certain ecological functions (e.g., pollination) can occur (Root et al. 2003; Visser and Both 2005). For example, climate change can reduce the amount of food available to birds during migration and the breeding season (Both et al. 2006; Leech and Crick 2007). It can also alter fundamental interactions between species that affect competition and survivorship (Root and Hughes 2005). However, the scale of response can depend on the life history of the individual species. For example, sea birds with high dispersal capacity have been shown to respond to broader-scale cues (e.g., the North Atlantic Oscillation) whereas permanent residents tend to response to local-scale cues (e.g., sea surface temperature) (Frederikson et al. 2004). Similarly, the timing of spring migration by long-distance migrants is more attuned to regional- to continental-scale climates while timing of spring migration by short-distance migrants responds much more strongly to the local climate (MacMynowski and Root 2007). Information on phenology can be found at http://www.usanpn.org/.

Population Growth Rates

Species that can quickly recover from low population numbers are more likely to be able to withstand rapidly changing climates as well as colonize new locations following climate disruption (Kinnison and Hairston 2007). In addition, rapid population growth can also help maintain genetic variability. This trait favors colonization of extant and novel habitats by early-successional and invasive species (Cole 2010). As a result, conservation practitioners and managers will be challenged by deciding which species have conservation value as species reassemble and populations grow.

Degree of Specialization

Generalist species are likely to be less sensitive to climate change than are specialists (Brown 1995). Species that use multiple habitats, for example, have multiple prey or forage species, or have multiple host plants are likely to be less sensitive to climate change than are species with very narrow habitat needs, single-forage or -prey species, or single-host-plant species (Thuiller et al. 2005). In addition, specialist species are likely to have specific evolutionary factors (e.g., low genetic variation for heat resistance) that limit their ability to adapt to changing conditions over time (Kellermann et al. 2009).

Reproductive Strategy

The reproductive strategy of species may also make them sensitive to climate change. Some studies suggest that species with long generation times and fewer offspring (e.g., “K-selected” species) are likely to be at greater risk of extinction under long-term climate change than those whose life history is characterized by short generation times and many offspring (e.g., “r-selected” species) (Isaac 2009; Chiba 1998). For example, more opportunistic, rapidly reproducing species may be better able to take advantage of major climate change–related disturbances such as wildfires and hurricanes.

Interactions with Other Stressors

The existence of other stressors has the potential to exacerbate the effects of climate change on individuals and populations. For example, research suggests that exposure to pollutants such as heavy metals, oil, and pesticides may act synergistically with ocean warming to induce coral bleaching events in some instances (Brown 2000). Studies have also found that the existence of pollution can significantly reduce the recovery rate of corals after major bleaching events and disease outbreaks (Carilli et al. 2009).

Habitat-Level Sensitivities

Sensitivity of Component Species

The sensitivity of a given habitat type will largely be determined by the sensitivities of its component species. The sensitivity of dominant species, ecosystem engineers, keystone species, and "strong interactors" are likely to have large influences on the sensitivity of a habitat type.

Community Structure

Plant and animal communities depend in part on a delicate balance of multiple, interspecific interactions. Some communities will be more sensitive to climate change than others. For example, the presence of algae-grazing species of fish and invertebrates can help limit the overgrowth of harmful, opportunistic algae on coral reef habitats damaged by coral bleaching, facilitating their ability to recover (Nyström et al. 2000). Coral reefs in regions where problems such as overfishing have reduced the population of algae-grazing species are therefore likely to be more sensitive to climate change than those with such functional communities intact.

The level of diversity of component species and functional groups in a habitat also may affect the sensitivity of that habitat to climate change impacts. For example, research suggests that restoring heterogeneity in vegetation structure, composition, density, and biomass to rangelands such as the tallgrass prairie of the Great Plains is likely to be an important strategy to improve the resilience of these systems to climate change (Fuhlendorf and Engle 2001). Increased homogeneity in some rangeland systems due to livestock production has made these systems much more vulnerable to disturbances such as widespread wildfires, which are different from the more patchwork-type burn patterns and associated grazing patterns of a more diverse tallgrass prairie system.

Ecosystem-Level Sensitivities

Sensitivity of Component Species

The sensitivity of a given ecosystem will largely be determined by the sensitivities of the ecological function and biological diversity of that system, as well as the sensitivities of the component species/habitats.

As with habitats, the sensitivities of dominant, keystone, and indicator species are likely to have large influences on the sensitivity of an ecosystem. For example, the ochre sea star is a keystone species in rocky intertidal ecosystems of the Pacific Northwest, in that it maintains community diversity through predation on mussels. Research has found that such predation is sharply reduced by decreases in water temperature (such as during the seasonal upwelling of cold, nutrient-rich water from the ocean floor) (Sanford 2002). Upwelling is sensitive to climate, and its frequency and intensity may be reduced by future climate change. As a result, predation by the ochre sea star may become more regular, transforming the community dynamics by reducing mussel populations.

Sensitivity of Ecosystem Processes to Temperature or Precipitation

Many ecosystem processes, such as decomposition, nutrient transport, sedimentation, fire, etc., are sensitive to changes in temperature or precipitation. Changes in river flow and water temperatures, for instance, are likely to have an impact on eutrophication and oxygen depletion in estuarine systems such as the Chesapeake Bay. If climate change leads to an increase in the frequency or extent of heavy downpours, as some models suggest, increased runoff will flush greater amounts of nutrients and other pollutants into coastal waters (Hagy et al. 2004). Heavy runoff also decreases water mixing as less dense fresh water rides over the top of denser salt water, inhibiting the mixing of water and the replenishment of oxygen in deep waters. Higher water temperatures also may affect oxygen levels in some systems because warm water holds less dissolved oxygen than cool water (Najjar et al. 2000). Further, higher water temperatures can accelerate the bacterial decay of organic matter present in the water, thereby consuming oxygen and exacerbating hypoxia (Varekamp et al. 2004).

Assessing Exposure

Universal Elements of Exposure

Most of the following exposure elements apply to all three levels of ecological organization. This section provides a general overview of the various elements of exposure. The following chapter (Chapter IV) offers more detailed information about specific tools available to evaluate exposure in climate change vulnerability assessment.

Historic versus Future Projected Change

Vulnerability assessment can be conducted either based on historic observed changes in climate (retrospective assessment), future modeled projections (prospective assessment), or a combination of the two. Historic changes will generally indicate the current vulnerability as compared with the past, while the future climate projections will give an assessment of future vulnerability. Depending on the objectives of the assessment, one or the other may be more appropriate. If the resources and data are available, a combination of both retrospective and prospective assessments provides the most complete picture in terms of the current status and the likely future status.

Basic Climate

The most basic and direct types of exposure are from changes in climate: temperature, precipitation, wind, humidity, cloud cover, and solar radiation. Although these variables often increase vulnerability indirectly—such as by changing hydrology, fire, or distribution of interacting species (e.g., competitors, predators, prey, etc.)—they can also directly increase vulnerability. The change in the mean values of these basic climate variables can be used in vulnerability analyses (e.g., changes in average annual temperature or total annual precipitation). However, it may be changes to the extreme values of these variables (e.g., daily minimum or daily maximum temperatures) that are most important for determining vulnerability. The ability for plant species to exist in a certain area is often related to the temperature of the coldest day of the year in that location.

These basic climate variables can be measured for different time periods—annually, seasonally, within specific months, or even within a day (e.g., nocturnal/diurnal extremes). Understanding which of these time periods and climate measures are biologically relevant is key for determining climate vulnerability. For example, changes to springtime temperatures may be the most important factor determining climate sensitivity for organisms or ecosystems dependent on the timing of specific spring events such as flowering or hatching. In contrast, wintertime temperature changes might be most important for a species with chilling requirements for seed production (Luedeling et al. 2009).

Drought

Changes in temperature and precipitation can influence drought frequency and/or severity. In general, it is thought that under climate change there will be an increase in the incidence, intensity, and duration of droughts, but this will certainly differ by location. There are drought indices available for quantifying the exposure to drought (Trenberth et al. 2003). Two of the most commonly used indices are the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI). For a good overview of drought indices see: http://drought.unl.edu/whatis/indices.htm. The U.S. Drought Monitor Program (http://drought.unl.edu/DM/MONITOR.html) provides current and recent historic maps of drought severity in the United States. The National Oceanic and Atmospheric Administration provides current drought maps at: http://lwf.ncdc.noaa.gov/oa/climate/research/prelim/drought/palmer.html.

Hydrologic Changes

There are many hydrologic changes that may occur to both terrestrial and aquatic systems in a changing climate. For terrestrial systems, the types of hydrologic exposure will generally relate to the amount of available soil moisture through changes in precipitation, water runoff, and evapotranspiration (ET). In general, increasing temperatures will result in increased rates of ET causing decreases in soil moisture. Increases in precipitation can offset this increase in ET, but it must come in sufficient amounts and at the right time of year. If temperature increases and precipitation does not change or decreases, it can be fairly safely assumed

USFWS

that soil moisture will decrease. There are various methods of calculating changes to ET. The simplest methods are based only on temperature and number of daylight hours (e.g., the Hamon method) (Hamon 1961). The assessment approach used in the Four Corners case study (Case Study 6) included application of the Hamon method. More complex methods for computing ET need information about temperature, wind speed, relative humidity, and solar radiation (e.g., Penman-Monteith) (Allen et al. 1998). Once ET is estimated, various related metrics can be calculated by subtracting it from ET from precipitation: actual ET, moisture deficit, and moisture surplus.

Macroscale hydrologic models provide an even more complex and generally more accurate but computationally intensive method for estimating hydrologic responses to climate change. One such model is the Variable Infiltration Capacity (VIC) model developed by researchers at the University of Washington (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/). These models explicitly track the movement of water through the landscape, and so are generally more accurate and complete than the other methods for estimating ET. In addition to the metrics mentioned above, these models can also model other hydrologic changes, such as snowpack depth and water runoff. The changes in water runoff can be used to estimate changes in river flow. Depending on how climate changes, river flow may change in different ways, but with warming temperature there are some changes that are more likely to occur, such as earlier spring runoff and lower summertime base flows in snow-fed rivers.

Changes in Fire Regimes

Climate change is expected to contribute to significant changes in fire regimes in some regions, including shifts in the timing, intensity, and frequency of wildfire events (Flannigan et al. 2000). For example, research shows that wildfires in western forests have become more frequent and larger since the mid-1980s, a trend that corresponds with warmer springs and an expansion of summer dry periods (Westerling et al. 2006). Studies project that the overall acreage burned could double in size across parts of the west by mid- to late century as average temperatures continue to rise (Spracklen et al. 2009; McKenzie et al. 2004).

Changes in CO_2 Concentrations

There is no doubt that atmospheric CO_2 concentrations have already increased from approximately 280 parts per million (ppm) in the recent historic past to around 385 ppm today. Future atmospheric CO_2 concentrations could range from 500 ppm to close to 1000 ppm based on emissions scenarios used in the IPCC AR4 (2007b). The concentrations will continue to rise through at least the late part of this century, and depending on the emissions scenario considered, concentrations may continue to increase beyond the end of the century. These changes in CO_2 concentrations can have physiological effects on plant species. For example, increases in atmospheric CO_2 concentrations can result in increased water use efficiency in some plants. In an atmosphere with enriched CO_2, these plants may be able to grow in drier climates than they currently occupy. Changes in water use efficiency can also lead to higher-level ecological impacts such as changes in species competitive interactions and changes to community composition (Cramer et al. 2001).

Changes in Vegetation

Changes in climate have the potential to alter the distribution of plant species and hence alter plant associations and plant communities. Dynamic global vegetation models and other less complex models can be used to project how "plant functional types" such as conifers, broad-leafed deciduous trees, and grasses are likely to change in the future (Bachelet et al. 2001; Cramer et al. 2001; Sitch et al. 2003). Projected shifts in vegetation types or biomes can provide an idea of how much specific plant community types might change.

Changes in Species Distributions

Species distributions will shift as climate changes. In some cases, it will be useful to understand how a specific species might move in response to climate change. For example, maps of projected range shifts for invasive species, keystone species or ecosystem engineers, or predators, competitors, or diseases of a focal species may serve as useful exposure elements for individual species, habitats, or ecosystems. Species distribution modeling can be used to project how species' ranges will shift due to the many different factors affected by climate change (Lawler et al. 2006, 2009).

Changes in Salinity

Climate change is altering salinity concentrations in the world's oceans. In the Atlantic Ocean, there has been an increase in salinity observed between latitude 20 and 50 degrees north (Stott et al. 2008), while increasing water runoff from melting glaciers and polar ice caps are causing a decrease in salinity in oceans near the poles (Curry et al. 2003). For a good overview of ocean salinity see: http://nasascience.nasa.gov/earth-science/oceanography/physical-ocean/salinity. Data and maps on changes to salinity can be found at: http://aquarius.jpl.nasa.gov/AQUARIUS/index.jsp.

Changes in pH

As the oceans absorb atmospheric CO_2, they become more acidic. If CO_2 concentrations in the atmosphere continue to increase at the current rate, then the oceans will become relatively more acidic (i.e., will have a lower pH) than they have been in millions of years (Caldeira and Wickett 2003). This lower pH will erode the basic mineral building blocks for the shells and skeletons of calcareous, reef-building organisms such as shellfish and corals, as well as a number of important microorganisms that are a foundation for the marine food web (Kuffner and Tihansky 2008; Orr et al. 2005).

Changes in Storm Frequency and Intensity

In general, the frequency and magnitude of intense storms is projected to increase. This is at least in part due to increased temperatures causing greater evaporation. For example, modeling studies have projected an increase in tropical cyclone (hurricane) intensity, and there is evidence that the number of Category 4 and 5 hurricanes has increased over the past 30 years (Trenberth 2007; Webster et al. 2005; Emanuel 2005).

Richard Maack/Fountain Studio

Assessing Adaptive Capacity

The IPCC defines adaptive capacity as "the potential, capability, or ability of a system to adjust to climate change, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (IPCC 2007c). In the context of assessing the vulnerability of human communities, adaptive capacity often refers to the potential to implement planned adaptation measures to cope with change, including factors such as economic wealth, institutional capacity, and equity (Metzger et al. 2005). For natural systems, adaptive capacity is often considered to be an intrinsic trait that may include evolutionary changes as well as "plastic" ecological, behavioral, or physiological responses (Williams et al. 2008). This is not to say, however, that only the intrinsic factors of adaptive capacity are relevant in assessing the vulnerability of species, habitats, or ecosystems to climate change. Certainly, there are likely to be a number of external factors (both natural and anthropogenic) that will influence the ability of a species or system to adjust to or cope with climate change (see Box 3.1). This section provides some examples of adaptive capacity within both of these contexts.

As mentioned earlier in this report, it is important to note that some of these examples may be considered as factors that contribute to a species or system's sensitivity to climate change, rather than as adaptive capacity.

Species-Level Adaptive Capacity

Plasticity

The ability for a species to modify its physiology or behavior to synchronize with changing environmental conditions or coexist with different competitors, predators, and food sources (a characteristic called *plasticity*) can be considered a factor of adaptive capacity (Running and Mills 2009; Nylin and Gotthard 1998; Gotthard and Nylin 1995). In general, plasticity increases the likelihood that a species will be able to respond effectively to both climate change itself and to effects of climate change, such as phenological mismatch (Parmesan 2005; Parmesan and Galbraith 2004; Parmesan et al. 1999). There is evidence that recent climate change has already elicited these types of adaptive responses across a wide range of plant and animal species (Walther et al. 2002). Over time, it is possible that these traits may become a genetic, evolutionary component (see below).

Dispersal Abilities

Dispersal refers to the movement of a species away from an existing, typically natal, population (Fahrig 2007). Some species may be able to disperse over long distances (e.g., seeds may be carried to different areas by birds or other hosts).

Other species, such as those that have evolved in patchy or rare habitats, may have lower dispersal ability. In general, species that are poorer dispersers may be more susceptible to climate change as they will be less able to move from areas that climate change renders unsuitable and into areas that become newly suitable. Berg et al. (2010) reviewed dispersal distances across broad taxonomic groups, noting especially that below-ground organisms tend to have an extremely limited ability to disperse. Barriers to dispersal may increase the vulnerability of some species with high innate dispersal ability.

Evolutionary Potential

Some species and some populations will be better able to adapt (evolutionarily) to climate change. Relevant traits include generation time, genetic diversity, and population size (Skelly et al. 2007; Bradshaw and Holzapfel 2006). For example, species with shorter generation times, in general, have faster evolutionary rates than species with longer generation times, and may be able to evolve behavioral or physiological traits that allow them to withstand climatic changes more rapidly than will than long-lived species with long generation times. Likewise, populations with high genetic diversity for traits related to climate tolerance are more likely to contain individuals with heritable traits that increase the tolerance of the species to climate change. Several recent studies have already discovered heritable, genetic changes in populations of some animals, including the Yukon red squirrel (Réale, et al. 2003), the European blackcap (Bearhop et al. 2005), and the great tit (Nussey et al. 2005), in response to climate change, most often associated with adaptation to the timing of seasonal events or season length.

Maintaining the evolutionary potential for species to adapt will be key in designing climate change adaptation strategies. Among the best approaches for retaining this potential is ensuring that protected area networks harbor a well-distributed representation of species found in a region.

Habitat-Level Adaptive Capacity

Permeability of the Landscape

The degree to which species, propagules, and processes can move through the landscape will affect the sensitivity of species, habitats, and ecosystems to climate change. More permeable landscapes with fewer barriers to dispersal and/ or seasonal migration will likely result in greater adaptive capacity for species, habitats, and ecosystems. However, the degree to which a landscape is permeable

USFWS

Box 3.1. Assessing Adaptive Capacity: Insights from a Coastal System

Both natural and anthropogenic factors can affect the adaptive capacity of a system, as illustrated in the case of coastal vulnerability to sea-level rise (Klein and Nicholls 1999). The impacts of sea-level rise on a coastal system depends on the global rate of eustatic sea-level rise, which refers to the change in volume of the oceans due to thermal expansion and the addition of water from land-based ice melt, as well as localized factors that affect the relative amount of sea-level rise in a particular area. Relative sea level rise is affected by such variables as rates of geological uplift and deposition of sediments: marsh sediment accretion, for instance, can lessen the amount of localized sea-level rise, while land subsidence can exacerbate the problem. In deltaic systems, for example, the release of river sediments downstream can help habitats such as coastal wetlands keep pace with sea-level rise (Reed 2002; Morris et al. 2002). Similarly, coastal habitats such as wetlands and beaches might be able to occupy new areas farther inland as rising sea levels inundate or erode those habitats along the shore. Essentially, these variables can be considered elements of the adaptive capacity of a coastal ecosystem.

A number of factors can either enhance or reduce this adaptive capacity. For example, altered river flows (due to climate change, upstream water uses, and/or other stressors) or the existence of dams or levees can reduce or eliminate the amount of sediments that reach the coast, contributing to a higher rate of relative sea-level rise. Similarly, the existence of upland barriers, either natural (e.g., rocky cliffs) or anthropogenic (e.g., seawalls), can limit or prevent the ability of coastal habitats to migrate inland. Ultimately, understanding the multiple factors that can affect the adaptive capacity of a coastal ecosystem can help inform relevant management decisions, such as finding ways to restore the deposition of sediments or removing coastal barriers.

depends on the process or organism that is being considered, and thus a permeable landscape for one species may not be very permeable for another species. The relative permeability of a landscape may depend on both natural and anthropogenic factors. In particular, fragmentation of habitat due to urban development, agriculture, dams, and other human activities is likely to be an important factor in reducing the adaptive capacity of some otherwise highly dispersible and migratory species (Vos et al. 2002).

Ecosystem-Level Adaptive Capacity

Redundancy and Response Diversity within Functional Groups

Within any community, there is a range of functional groups present. In ecological communities, this includes groups such as primary producers, herbivores, carnivores, and decomposers. In systems where each functional group is represented by multiple species and the response to any given environmental change varies significantly among the species that make up the functional group, system resilience to environmental change is likely to be higher (Nystrom et al. 2008; Naeem 1998; Petchey and Gaston 2009). In other words, if a particular species or decomposer responds negatively to a climate change but others respond positively, decomposition function within the system may not be disrupted.