4.25 Mitigation and Adaptation Strategies to Reduce Climate Vulnerabilities and Maintain Ecosystem Services

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Glossary

Adaptation Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation (IPCC 2001).

Climate change A significant and lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years. We focus largely on changes in temperature and precipitation, as they are changing in many regions and have direct impacts on ecosystems and human well-being.

Mitigation Actions that reduce the effects of humans on the climate.

Resilience Amount of change a system can undergo without changing state (IPCC 2001).

Sensitivity It is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise) (IPCC 2001).

Vulnerability The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC 2001).

4.25.1 Introduction

Virtually all regions of the earth are experiencing rapid changes in temperature, precipitation, and/or other aspects of climate. Human-caused changes in the earth's climate are greatly altering ecological systems, with consequences for human well-being. For example, recent studies have documented shifts in the distribution of plants and animals, advances in the timing of key ecological processes, and extinctions of wildlife populations and species that are likely linked to recent increases in temperature (Parmesan 2006). Such changes are creating regional combinations of environmental conditions that, within the next 50–100 years, may have no current-day analog. The resulting changes in ecosystem function will undoubtedly affect the provision of ecosystem services for human communities.

Maintaining or increasing ecosystem services into the future will require integrating adaptation strategies (actions that help human and natural systems accommodate changes) and mitigation strategies (actions that reduce anthropogenic influences on climate) (Figure 1). Mitigation strategies are those that reduce the magnitude of climate change that will occur. The vast majority of these strategies involve either reducing greenhouse gas (GHG) emissions or sequestering carbon, although they can address any human climate forcing. By contrast, adaptation can be defined as
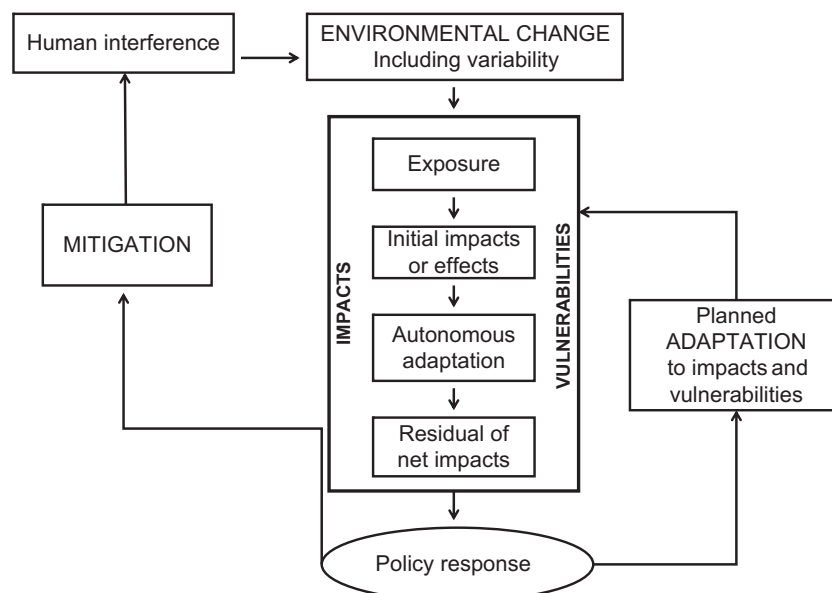

Figure 1 Conceptual diagram of vulnerability, mitigation, and adaptation options associated with climate change. Source: IPCC, 2001: *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Table 1   Examples of mitigation strategies aimed at reducing GHG emissions or, in the case of the last category, sequestering carbon to reduce CO_2 concentrations in the atmosphere

Sector	Mitigation strategies	Barriers to implementation
Transportation	Walkable and bikable communities	Lack of safe bike paths
	Increased vehicle efficiency	Political lobbying of car industry
		Lack of public transportation
		Poorly designed communities (sprawl)
		Cultural values
Shelter	Alternative building materials	Lack of incentives
	Passive solar heating	Restrictive building codes
	Daylighting	Cost of alternative materials
Food	Changes in diet	Cultural values
	Increased soil organic matter	Mass media
		Demand for low-price food
Energy	Renewable sources	Cost of new technologies
	Reduced consumption	Political lobbying of the energy industry
Carbon sequestration	Reforestation	Subsidized clear cutting
	Reduced deforestation	

alterations to human or natural systems that are designed to reduce the negative impacts of – or exploit the opportunities created by – climate change (IPCC 2007a). Adaptation strategies are much more varied than mitigation strategies, as they are more often specific to particular systems or locations.

Mitigation and adaptation strategies designed to address changes in climate may have additional positive or negative effects on ecosystem functioning, ecosystem services, and human well-being. For example, replacing fossil fuels with renewable energy sources reduces GHG emissions while simultaneously reducing air pollution, acid rain, and smog, as well as asthma and respiratory ailments of humans. Conversely, coastal armoring, the building of seawalls, breakwaters, and jetties, may reduce damage to built structures from the combined effects of sea-level rise and storm surges but such actions can negatively affect coastal ecosystems.

In this chapter, we provide an overview of what will likely be some of the most effective and most important mitigation and adaptation strategies for addressing changes to the climate system stemming from increased GHG emissions. We attempt to cover the entire spectrum of life, from plants and animals to humans, as well as the geophysical properties of our planet that support these organisms. In relation to human populations, we focus primarily on human health as an index of well-being. We also introduce concepts of climate justice. Many of our examples are taken from the United States, although we also include other regions of the world in our analysis as appropriate. We discuss various ways in which mitigation and adaptation strategies can help reduce the magnitude and the impacts of the changes we are likely to experience, as well as improve human health and directly or indirectly affect ecosystem functions and services. Finally, although our analysis sets priorities and orders of importance for an ideal world unimpeded by political considerations, cultural differences, or economic limitations, we include a discussion of the social considerations that we believe must be incorporated into the development and application of mitigation or adaptation strategies.

4.25.2   Mitigation

In the following sections, we briefly discuss what will likely be some of the most effective mitigation strategies for addressing climate change, largely focusing on strategies to reduce CO_2 and other GHG emissions (Table 1). We have grouped these strategies into five categories: transportation, shelter, food, energy, and carbon storage and bioengineering. Although we focus on mitigation strategies that will reduce the magnitude of future climatic changes, we also discuss how these strategies can improve ecosystem functioning and, in some cases, human health.

4.25.2.1   Transportation

Transportation, the movement of people and goods, significantly impacts climate through the emission of GHGs. In 2004, transportation accounted for 23% of the world's energy-related GHG emissions and road transportation represented 74% of the total carbon dioxide (CO_2) emissions from transportation (IPCC 2007b). In addition to being a major source of emissions, transportation also significantly affects ecosystem functions and services. Pollution from vehicles affects ecosystem services such as clean air and water directly, and indirectly through impacts on the plants and animals that regulate ecosystem function. As species are lost from or move into ecosystems the functioning of those systems can change, resulting in altered ecosystem services. Human health is likewise affected by pollution from vehicles (e.g., through chronic lung disease). Transportation networks and moving vehicles also fragment landscapes, reducing the flows of energy and biota resulting in isolated populations and potentially making these populations vulnerable to extirpation and impairing ecosystem functions.

Mitigation strategies that address transportation can be placed into three basic categories: those that increase the efficiency of particular transportation approaches, those that result in a shift in the mode of transportation, and those that reduce the amount of transportation that is needed. Here, we briefly

summarize some of the most important mitigation strategies for each category.

4.25.2.1.1   Vehicle Efficiency

A large reduction in GHG emissions can be accomplished by increasing the fuel efficiency of vehicles. For example, increasing the efficiency of light-duty vehicles (cars and small trucks) has the potential to reduce their carbon emissions by up to 50% by 2030 (IPCC 2007b). Such efficiencies can be attained by a combination of reducing vehicle weights, increasing aerodynamics, increasing engine efficiency (particularly diesel engine efficiency), and increasing the use of biofuels and electric and hybrid vehicles. In 2006, the International Energy Association projected that the proportion of transportation energy supplied by biofuels could be increased to 10% (IEA 2006a). Although there is good evidence of successful biofuel markets and programs (e.g., ethanol from sugarcane in Brazil, Goldemberg 2007), there are also negative consequences of increased biofuel production for biodiversity and carbon storage (Fargione et al. 2008; Fletcher et al. 2010). One opportunity for transportation mitigation strategy is the promotion of behavioral changes of drivers. Efficiency of road vehicles could be improved by 5–20% by changes in driving styles, improved maintenance, more efficient tires, reduced idling, and traffic design and maintenance (IPCC 2007b).

4.25.2.1.2   Modes of Transport

A second approach to reducing emissions and many of the other effects of transportation involves changing the ways in which people and goods are moved. One such approach is to increase the use of public and human-powered transportation. Increasing the amount of walking, biking, and use of public transit will depend largely on the available infrastructure and the capacity to provide it. Supporting the development of 'walkable' cities and neighborhoods, bike-friendly roadways and bike paths, carpooling and car-sharing programs, and efficient and safe mass transit are all approaches for shifting the mode of urban transport.

Present transportation alternatives vary by country, with Europe, Japan, and many developing countries having the highest levels of public transportation use, and the United States having the greatest use of personal automobiles. In some developing countries, such as Vietnam or China, personal automobile use is a recent phenomenon, and personal motorized transport is a high aspiration because it conveys increased social status. This disparity in the historical development of the transportation sector will mean that mitigation strategies, barriers, and solutions will have to be location specific and may be dynamic over time.

In addition to the reduction in emissions and the other environmental benefits of shifts to more human-powered transportation, such changes also have clear human health benefits resulting from increased exercise, weight management, and decreases in air pollution (Nemet et al. 2010). Simultaneously improving the quality of public transport and leap-frogging transport-intensive stages of economic growth is needed in many countries to increase higher levels of mass transit use and human-powered transportation (Wright and Fulton 2005). Further reductions in emissions can be made by changing modes of transport for other transportation such as moving more freight by train and ship and less by truck.

4.25.2.1.3   Transportation Demand

The third way to reduce transportation-related GHG emissions is to reduce the amount of transportation that is needed. Decreasing the demand for transportation largely involves changes in human behavior, urban and landscape planning, and changes in technology. Sprawling, low-density urban neighborhoods, such as those found in the United States, perpetuate automobile dependency and transform ecologically functional landscapes into subdivisions. Compact, high-density communities with local urban centers allow residents to work and live in close proximity, and help build social capital among residents and protect natural areas. In conjunction with human-centered transportation infrastructure such as sidewalks, bike lanes, and public transportation, compact neighborhoods reduce car dependency while simultaneously improving the physical fitness of residents. Public green space and urban forests sequester carbon while improving air quality and mental well-being. Increased vegetation, shade trees, and less asphalt combat urban heat-island effects and reduce energy demand for cooling buildings.

Advances in communication technologies also have the potential to reduce the need for transportation. The Internet, online meeting, document sharing, and conference tools have led to an increase in telecommuting and web-based meetings. Similarly, online meetings have begun to replace some in-person meetings and have the potential to dramatically reduce air travel, which can account for a significant portion of an individual's carbon footprint (Fox et al. 2009).

4.25.2.1.4   Barriers and Opportunities

The most significant barriers to implementing mitigation strategies in the transportation sector are long-established personal transportation behaviors and the lack of government interest or capacity to invest in new technologies. Changing the way and the amount that people move around will be very difficult. In the United States and elsewhere, people's relationships with the automobile involve issues of convenience, independence, safety, and social status. Changing these relationships will involve making forms of public transportation more convenient, more effective, and more appealing. Rising fuel costs and commute times may provide some opportunity for implementing transportation-based mitigation strategies. Failing automobile industries and economic crises may provide another. Similar to the projects undertaken by the Civilian Conservation Corps in the United States in the depression of the 1930s, modern-day work relief programs could be used to transform transportation systems. Short of such crises, major changes in transportation will take a combination of regulatory action, education, and incentive programs.

4.25.2.2   Shelter

Housing is one of the most idiosyncratic and regionally variable aspects of human culture. The design of structures is dependent on local climate, land access, available materials, and regional architectural histories. Much of the recent human-caused change in climate stems, in large part, from the way we design, construct,

and inhabit the built environment. The following section focuses on a representative selection of design strategies that mitigate the built environment's contribution to carbon emissions and, in many cases, provide cobenefits to human health and local/regional ecological resilience.

4.25.2.2.1   Carbon-Conscious Materials

Building material extraction can have profound impacts on ecosystems and ecosystem services. Mining degrades natural landscapes, destroys habitat, pollutes freshwater environments, and can expose human populations to toxins. Poorly managed lumber extraction leads to deforestation, eliminates suitable habitats, erodes soils, and diminishes the earth's carbon sequestration capacity. Mines that observe best management practices such as land reclamation have fewer negative impacts on climate, local ecosystems, and human health. Sustainably harvested lumber can act as a long-term carbon sink and contribute to the productive and ecological resilience of forests. Rapidly renewable lumber alternatives such as bamboo can offset the demand for slow-growing trees species, rebuild soils, and set the stage for reforestation. However, as with any renewable resource, expanding the production of bamboo in monocultures has the potential to eliminate and/or degrade existing ecosystems.

Eight percent of annual carbon emissions worldwide can be attributed to building material extraction, production, transportation, and installation (Mazria and Kerschner 2008). Choosing building materials with low embodied energy (the cumulative energy of extraction, production, transport, installation, and disposal) and/or that use alternative energy sources reduces the building sector's carbon footprint. Locally sourced materials produce fewer carbon emissions than those transported long distances and both durable materials and those with recycled content help reduce demand for virgin materials. Fully recyclable materials can be reprocessed and repurposed with low energy inputs indefinitely. Removing toxic compounds from material production processes and building products facilitates the recycling or biodegradation of building components. It also helps prevent air and waterborne industrial pollution and associated human illness.

In some cases, it may be possible to choose building materials that actually sequester more carbon than is emitted in their production. The production of Portland cement, the most commonly used cement in construction, is a relatively large source of CO_2 emissions. Magnesium oxide-based cement is as strong as normal Portland cement, but can be manufactured at low temperatures using renewable energy sources. Magnesium oxide is an abundant mineral and is easily recyclable (Smith 2005). As it cures, it absorbs more CO_2 than is released during its production, resulting in a net negative carbon budget.

4.25.2.2.2   Regenerative Buildings

The average lifespan of buildings in the United States is less than 50 years (O'Connor 2004). Design for adaptation – design that easily accommodates changes in configuration and use – extends the life of buildings and stems demand for new construction and virgin materials. When buildings are ultimately decommissioned, design for disassembly facilitates the breakdown and reuse of their constituent components. Both design for adaptation and design for disassembly act upstream

from recycling as part of a multicyclic system that repositions well-weathered buildings and building materials as resources rather than wastes, reducing carbon emissions in the process.

Building operations such as heating, cooling, and lighting account for 42% of electricity consumption in the United States (Mazria and Kerschner 2008). Passive design strategies can drastically reduce a building's dependence on carbon-intensive energy production. In cold climates, airtight, well-insulated building envelopes can work in tandem with building orientation, thermal mass, and passive solar radiation to provide thermal comfort and reduce heating bills. In hot climates, external shading, light colored/reflective roofs and walls, and passive ventilation strategies can reduce cooling loads. Daylighting strategies such as light shelves and shallow floor plans bring natural light into interior spaces, reducing the demand for electrical lighting while, at the same time, contributing to the well-being and productivity of building occupants.

Similar to the use of building materials to sequester more carbon than they produce, buildings can generate more energy than they consume. Buildings equipped with photovoltaics, wind turbines, and fuel cells are some of the energy producing technologies that make this possible. Recent advances in computer-aided design software help designers address building performance issues early in the design process and optimize building design for energy use and production. Improvements in digital monitoring and analysis allow occupants to scrutinize building performance and optimize energy use once buildings are operational. In the future, smart buildings and systems will likely respond dynamically to human occupation, weather, daily cycles, and seasonal change, further reducing their energy footprint.

4.25.2.2.3   Compact Communities/Integrated Landscapes

Compact communities (discussed in the transportation section, above), land-use planning, and high-density zoning have the potential to reduce CO_2 emissions, reduce sensible and latent heat fluxes, and improve human health and ecosystem function. Centralized infrastructure and zoning laws that segregate industrial, commercial, agricultural, and residential land use can be beneficial to public health within localities. However, these practices also create a cognitive disconnect between human action and its environmental consequences. They facilitate the transfer of local environmental burdens to regional and global scales, contribute to climate change, and undermine the health of vulnerable populations. Integrated land use and responsibly managed distributed ecological infrastructure have the potential to safeguard public health without the transference of environmental burdens. Synthesizing commercial, industrial, agricultural, and residential precincts, reimagining landscape as infrastructure, and bringing utilities into the public realm raises awareness about the causal relationships that link human activities, environmental degradation, and human health. Urban agriculture, for example, reduces dependence on carbon-intensive industrial food production, minimizes the carbon footprint of food transport, teaches urbanites how to grow their own food, and provides nutrition to communities.

Carbon-conscious materials, regenerative buildings, compact communities, and integrated landscapes have the potential to mitigate the worst effects of climate change. Their success will depend on the ability to implement them not only in developed

countries but also in the burgeoning cites of the Global South. We must adapt these strategies to diverse climates, contexts, and cultures and pursue them in tandem with issues of economic development and social equity.

4.25.2.2.4   Barriers and Opportunities for Housing Mitigation Strategies

In modern history, land distribution and regulation have always been the prerogative of governments. For this reason, national, regional, and local governments have a large role to play in housing mitigation strategies. Governments control land-use planning, zoning, and building-code regulations. The ability to act on the mitigation strategies identified above, therefore, is largely dependent upon the regulatory and enforcement environment in a region. In a democratic society, these will in turn be dependent upon the inclination and ability of the state to assume progressive and proactive attitudes toward mitigation.

4.25.2.3   Food

Agriculture releases considerable amounts of GHGs into the atmosphere. In 2005, it accounted for 10–12% of the total global anthropogenic GHGs including approximately 60% of nitrous oxide (N_2O) and 50% of methane (CH_4) of the anthropogenic totals (Rosenzweig and Tubiello 2007; Smith et al. 2008; Burney et al. 2010). Land-use change, nitrogenous fertilizer applications, livestock production, rice farming, and biomass burning are among the major direct sources of GHG emissions. Indirect sources of GHGs from agriculture include the production and/or applications of fertilizers and pesticides, the operation of farm machinery, and the transportation of agricultural products (Burney et al. 2010).

There are multiple opportunities for mitigating climate change impacts through modifications in agricultural practices and food consumption. With respect to agricultural production, mitigation strategies include soil carbon sequestration and the reduction of GHG emissions through altered production methods. With respect to food consumption, society can mitigate the impacts of climate change through changes in diet and by reducing the amount of transportation needed to deliver food (e.g., increasing local food production). Below, we discuss several of these mitigation strategies. The topic of increasing local food production is covered in previous sections on transportation and shelter.

Unlike housing, food is a sector that is potentially much more amenable to individual decision-making and personal choice. This will depend on the relative proportion of food in a household budget. While Americans spend only 5% of their incomes on average on food, the figure for Indonesia is 30%. This indicates that people from wealthy countries would have greater flexibility to support alternative and nonindustrial agriculture through consumer preferences than those from countries where food is a larger part of household budgets.

4.25.2.3.1   Soil Carbon Sequestration by Soil Organic Carbon Management

Agricultural and degraded soils can act as large carbon sinks with the potential to sequester 55–78 Gt of carbon globally (Lal 2004). Soil organic carbon (SOC) is the major component (62%) of this large soil carbon pool (Lal 2004). SOC

accumulation is facilitated by adding biomass to the soil and minimizing soil disturbances. The increased SOC improves the physical, chemical, and biological properties of the soil and in turn enhances crop productivity, water holding capacity, and land sustainability under a low-input cropping system. Several agricultural practices facilitate accumulation and retention of SOC in cropland soils, e.g., conservation tillage, mulches, cover crops, manuring, crop rotations, and agroforestry (Lal 2004).

The benefits of these agricultural practices go beyond carbon sequestration. They have the potential to reduce erosion, limit positive feedbacks in drought cycles, and benefit human health. Over the past 40 years, 30% of the world arable land has been taken out of production as a result of erosion (Pimentel 2006). Conventional agricultural practices involving frequent tillage result in soil erosion, which in turn increases concentrations of airborne particulates. These particles can carry pathogens causing infectious diseases and can provide positive feedbacks to drought conditions. Recent climate modeling has demonstrated a positive feedback in the 'dust bowl' drought of the 1930s in the United States (Schubert et al. 2004; Cook et al. 2009). Cook et al. (2009) discovered that a reduction in vegetation cover and the addition of eroded soil dusts to the air resulted in a high temperature anomaly over the northern United States and intensified the drought. As a result of the dust bowl, more than 50% of the surveyed farms comprising 8.7 million acres were seriously eroded, and the economic loss was valued close to US$200 million (AAAS 1936). A combination of warming, drought, and conventional agricultural practices together have the potential to re-create the dust bowl of the 1930s in the Great Plains of the United States (Rosenzweig and Hillel 1993).

4.25.2.3.2   Reduction of GHG Emissions Associated with Livestock Production Systems

The livestock industry is a main contributor to three major climate-related problems associated with global food systems: GHG emissions, reactive nitrogen mobilization, and plant biomass appropriation (Pelletier and Tyedmers 2010). Increases in livestock production and meat consumption are also blamed for the evolution of new and virulent emergent diseases. Any improvement in the environmental sustainability of livestock production will concurrently have a benefit for human health.

Pelletier and Tyedmers (2010) estimated that globally the livestock sector contributed 14% of anthropogenic GHG emissions, 63% of reactive nitrogen mobilization, and consumed 58% of human-appropriated biomass as of 2000. Reduction in GHG emissions in agriculture can be achieved by developing strategies involving improved production efficiency, land-use changes, cropland and rangeland management, and livestock and manure management (Rosenzweig and Tubiello 2007; Smith et al. 2008; Burney et al. 2010; Pelletier and Tyedmers 2010). For example, enhancing production efficiency through agricultural intensification has been credited with the avoidance of 161 Gt of carbon emission globally since 1961 (Burney et al. 2010). This figure highlights that the investment in agricultural research to improve the environmental sustainability of global food production systems (i.e., livestock, crop, and aquatic systems) should be a prioritized mitigation strategy (Lobell et al. 2008; Burney et al. 2010;

Steinfeld and Gerber 2010). Another mitigation strategy to reduce emissions involves shifting livestock production regimes from ruminants to more efficient and lower impact monogastric species (e.g., poultry), well-managed fisheries and aquaculture, and promoting plant-based protein sources (Pelletier and Tyedmers 2010; Steinfeld and Gerber 2010).

4.25.2.3.3 Diet

Changing livestock production from ruminants to monogastric animals and reducing livestock production overall both require significant changes in diet in many parts of the world. This is, of course, where tradition and culture play an important role, yet it is not impossible to induce dietary changes.

Initiatives that reduce the consumption of meat could have dramatic effects on GHG emissions particularly in developed countries (McMichael et al. 2007). Such policies would also reduce impacts on ecosystems and promote other ecosystem services such as a reduction in the clearing of Amazonian rain forests, reduced nitrogen deposition, and a reduction in the application of high-phosphate fertilizers used to grow feed. Reduced meat consumption could also improve human health in developed countries particularly when coupled with incentive structures and educational measures to replace high-fat, sugar-rich foods with more complex diets based on plant proteins. Reduced red meat consumption will likely lower the risk of obesity, diabetes, and several types of cancer (and specifically colorectal cancer), and may reduce the risk of ischemic heart disease (McMichael et al. 2007).

A shift from meat-based proteins to plant-based proteins has the potential to substantially increase the total food calories available for consumption worldwide. Worldwide educational efforts, altered trade policies, shifts in farm subsidies, public health campaigns and new environmental stewardship programs will be needed to achieve a fundamental change in the consumption of meat to achieve large-scale cobenefits for the environment and human health.

4.25.2.4 Energy

Energy consumption and production affect carbon emissions, which in turn affect human health and ecosystem functioning and services. These effects can be divided into the influence of energy consumption and production. While human well-being is in many ways positively affected by the increased availability of energy, there are also negative health effects resulting from the energy consumption and production. Below, we describe potential mitigation strategies for the energy sector.

4.25.2.4.1 Energy Consumption

The US Energy Information Administration reports on energy consumption in the United States in four sectors: residential, commercial, transportation, and industrial. In 2009, consumption across the four sectors accounted for 22, 19, 29, and 30% of overall energy consumption, respectively (US Energy Information Administration 2010). Overall energy consumption, as well as CO_2 emissions from energy consumption, continues to rise. Total US CO_2 emissions from energy consumption were 1390 million metric tons of carbon in 1990 and 1586 million metric tons in 2008 (Research and Innovation Technology Administration 2011).

Reducing GHG emissions through declining energy consumption can be accomplished through a combination of technological advances and changes in human behavior (including the adoption of new or alternative technologies). Several mitigation strategies for addressing energy consumption have been provided in the previous sections on transportation and shelter. In addition to those strategies, increasing the efficiency of appliances and lighting is likely to provide significant reductions in GHG emissions. The most efficient appliances in use today use half to one-fifth of their most inefficient counterparts currently in use (IPCC 2007b). In developed countries, substituting smaller and more efficient refrigerators, washing machines, and other appliances for less efficient ones can substantially reduce energy use. In addition, in developed countries, improvements in the efficiency of electronic devices with inefficient standby modes and power supplies (or more simply unplugging these devices when not in use) can significantly reduce energy consumption. In developing countries where biomass (e.g., wood, dung, and charcoal) is used for cooking fuel, substantial reductions in GHG emissions and improvements in human health may be attained by increasing the efficiency of biomass stoves, fostering a shift to cleaner burning liquid and gaseous fuels, and improving access to electricity (IPCC 2007b).

Significant reductions in emissions can also be made through the use of more efficient lighting. The emissions from electric lighting worldwide are equivalent to roughly 70% of those generated by light passenger vehicles (IEA 2006b). Substituting more efficient lighting technology (e.g., compact fluorescent bulbs and occupancy detectors) can reduce residential energy use by a factor of four or five (IPCC 2007b). Programs designed to increase the energy efficiency of appliances, vehicles, and lighting (e.g., the Energy Star and vehicle fuel economy (CAFÉ)) also have the potential to reduce GHG emissions. Although such programs have not decreased energy use in the United States, they may be partially responsible for halting the growth of per capita energy consumption (US Energy Information Administration 2009).

4.25.2.4.2 Energy Production

Methods for reducing the impacts of energy production on atmospheric CO_2 concentrations, human health, and the environment focus primarily on improvements in an increased generation of renewable energy. Renewable energy sources include those based on waves and tides, biofuels, solar, wind, and hydropower. A shift to renewable energy sources has great potential to reduce GHG emissions, reduce impacts on ecosystems and ecosystem services, and improve human health. Nonetheless, the production of renewable energy will have adverse effects on some ecosystems. Below, we discuss some of the benefits and potential side effects of some sources of renewable energy.

In regions of large tides and tidal currents, such as the United Kingdom, tidal energy could supply as much as 10% of the country's energy supply (Blunden and Bahaj 2007). Two types of systems are in use or are proposed, the tidal barrage and tidal turbines. Tidal barrages allow water to flow into a bay or estuary during flood tide, then they release the water back during ebb tide. As water is released it flows through turbines generating energy. The impact of barrages on fish may be

substantial (Aprahamian et al. 2010). Power can also be extracted in the marine environment by turbines in regions of high wave and current energy. However, the ecological impact of the extraction of energy in highly energetic environments is not clear (Shields et al. 2011). The effects of such installations include alteration of benthic (ocean bottom) environments through changes in sediment transport and detrimental impacts on intertidal species through altered currents and nutrient flows.

Biofuels (discussed briefly in Section 4.25.2.1 Transportation) include corn- and sugarcane-based ethanol, wood-based methanol, biodiesel from soy, rapeseed oil, and switch-grass. Biomass is also used in cofiring (combining with coal or other fossil fuels in the burning process) or burned alone as a fuel. Crops can be grown explicitly for biofuels, or residues from farming or forestry can be used as biofuels. Biofuels can also be converted into gasses and then used to fuel gas engines. Nonetheless, many biofuels require significant amounts of land and water to grow them, which brings fuel production into conflict with food production as well as potentially result in a climate effect from the alteration in the surface fluxes of heat and moisture into the atmosphere. In addition, fuel plants may not be as effective as others at absorbing GHGs, and more natural lands converted to agriculture for biofuels will result in increased erosion, decreased water quality, and a loss of wild-life habitat and biodiversity.

Solar energy can be used to generate electricity, heat water, and heat buildings and can be a highly effective form of renewable energy in some regions. Although photovoltaic power generation only accounted for 0.004% of world power production as of 2007, expansion is occurring at roughly 30% per year, largely in developing countries (IPCC 2007b). Hot water production is the second single largest use of energy in residences in both the United States and China. Solar water heating is a cost-effective alternative to other fuel sources in many locations. Similarly, passive solar heating of buildings (mentioned in the Section 4.25.2.2 Shelter) is an effective heating measure in many regions. Finally, solar energy can be used to generate power with solar thermal electric plants that focus solar rays to heat a liquid, which is then used to generate electricity. Passive solar space heating and hot water production likely have the lowest environmental costs. Decentralized photovoltaic use on residences and buildings incurs environmental costs in terms of the production process, but likely have few other negative effects. Conversely, photovoltaic fields and solar thermal electric plants can have large footprints, adversely affecting plant and animal habitat.

Like solar power, wind-generated power is more effective in some areas than others. Wind produced 0.5% of global electricity in 2004 but has been growing at a rate of approximately 28% per year since 2000 (IPCC 2007b). There are potential adverse effects on birds, through collision, displacement due to disturbance, barrier effects, and habitat loss, with more research needed in all areas (Drewitt and Langston 2006; Fox et al. 2006). In addition, the impact of wind turbines on views is perceived to be a substantial barrier to implementation in some communities (Wolsink 2007).

As of 2004, hydropower accounted for 16% of global electricity (IPCC 2007b). Together, large hydropower plants and small and micro hydropower systems can supply power to large municipalities and isolated rural communities with relatively few emissions. Hydropower is not carbon neutral, however, and some studies have estimated significant emissions from hydropower reservoirs (IPCC 2007b). In addition, dams and reservoirs fragment river networks, alter natural flows of water and sediments, and change stream temperatures. These effects are discussed in Section 4.25.3.5 Human-Dominated Systems.

There are several other major renewable energy sources including nuclear, hydrogen, and geothermal. As with the renewable sources described above, there are both benefits and costs to using these other renewable energies.

4.25.2.5   Carbon Sequestration and Geoengineering

Most of the mitigation strategies discussed above are focused on reducing GHG emissions. Additional strategies can be used to increase carbon sequestration, removing CO_2 from the atmosphere. Below, we discuss a few strategies that have been proposed for increasing carbon sequestration and storage as well as much riskier geoengineering proposals.

4.25.2.5.1   Forest Protection Reforestation

Deforestation is one of the largest sources of emission accounting for over 8 Gt CO_2 per year in 2000 (Stern 2006). Although there are many other uses of natural resources that result in carbon emissions, here we focus on mitigation strategies that focus on deforestation. Given the slow rate at which trees absorb carbon dioxide, simply planting new trees in place of those removed does not immediately offset the removal of a tree. A more rapid approach to mitigation is to reduce deforestation. Unlike the majority of emissions that emanate from industrialized countries, most emissions from deforestation are generated by developing countries. Deforestation also itself alters the climate system (Pielke et al. 2007).

Reduced Emissions from Deforestation and forest Degradation (REDD+) is a program of the United Nations that seeks to mitigate climate change by providing incentives to conserve forest cover. Given recognized challenges in REDD (Dickson et al. 2009) – including country by country differences in who owns the forest, who should receive the monetary benefits of preserving the forest, and the reliance of various indigenous groups on forests for livelihood and cultural identity – the program was modified to REDD+ in 2010 to minimize negative consequences and respect the rights of indigenous peoples and members of local communities (Kanninen et al. 2010). Assumed cobenefits include the suite of ecosystem services such as watershed protection; reduction of soil erosion; flood control; provision of fuel, timber, and foods; and cultural and spiritual amenities for local communities. Biodiversity is presumably also enhanced by protecting natural systems. It is possible that forest-dependent communities will be able to maintain access to forests through this initiative. Potential co-harms are increased demand for conversion of other ecosystems if forests are protected, replacement of mixed stands with plantations, and benefits accruing to those not responsible for care and maintenance of the forests.

Prevention of deforestation mitigates atmospheric CO_2 concentrations by preventing the release of stored carbon that occurs when forests are harvested and protecting forest stands that absorb carbon, as well as limits changes in surface energy

Table 2   Examples of adaptation strategies that allow ecosystems and human communities to adapt to uncertain future environments

System	Adaptation strategies	Barriers and challenges
Freshwater	Increasing connectivity	Slow uptake of private–public partnerships
	Riparian restoration	for restoration
Terrestrial	Protected areas	Land costs
	Connectivity	Extent of land development
		Property rights arguments
Coastal	Coastal restoration and protection	Few demonstration projects
	Translocation of people and ecosystems	Demand for coastal development
Human dominated	New dams	Growing demand for food
	Shifts in the distribution of agriculture	Growing demand for water

and water fluxes. As of 2011, South America and Africa continue to have the largest net loss of forests and large decreases in carbon storage (FAO 2011). Although tropical forests have been the focus of early REDD efforts, recent evidence indicates that a large amount of carbon can be stored in mangrove forests (Donato et al. 2011), peatlands (Dise 2009), and boreal forests (Carlson et al. 2010), making these potential targets for conservation efforts. Urban forests have also been largely neglected as a potential carbon sink. Escobedo et al. (2011) review the services and disservices of urban forests combined with human health and pollution mitigation as well as carbon sequestration. In some locations, urban forests are on par with other techniques for carbon sequestration and reduction.

4.25.2.5.2   Other Forms of Carbon Capture
In addition to capturing carbon in plants, it may be possible to increase carbon storage in the water and in the earth's crust with various methods. These proposed approaches are still on the scientific fringe and considered to be highly unproven and/or potentially quite risky. One such approach is to capture carbon in the oceans through iron fertilization. In regions of the ocean where there are ample nutrients to drive primary production (photosynthesis) but observations show that chlorophyll is relatively low, the lack of iron is thought to limit the productivity. Over the last two decades, several experiments have attempted to determine whether the addition of elemental iron into the water could cause an increase in algal production and ultimately, as photosynthesis fixes carbon into organic molecules that then sink, the sequestration of carbon in deep ocean sediments. However, the results of these experiments are mixed (de Baar et al. 2005), with the export of carbon being difficult to assess and likely quite modest. At the same time, the impacts on local ecosystems and thus ultimately fisheries in potentially highly productive regions of the subpolar oceans are not yet known. Other carbon sequestration approaches have also been proposed including pumping air down into the oceans, injecting carbon into the ground, and incorporating biochar into soils.

4.25.2.5.3   Geoengineering
Given the magnitude of projected changes in climate and the difficulty in implementing meaningful mitigation measures, some scientists have argued for large-scale efforts to reduce the amount of incoming solar radiation. These approaches are collectively referred to as geoengineering. At present, these approaches are unproven, risky, and, at best, will only address some of the impacts of the human influence on climate. One

such geoengineering approach would inject sulfate aerosols into the stratosphere. These aerosols would reflect incoming solar rays and reduce warming. Although such an approach might reduce average global temperatures, it would also likely decrease average global precipitation (Bala et al. 2008) as well as alter atmospheric and ocean circulation patterns. For a given change in radiative forcing, solar forcing is more effective at changing the hydrological cycle than forcing from carbon dioxide owing to differences in the surface latent heat (and thus evaporation) response. While the impact of carbon dioxide fertilization could increase net primary production in terrestrial ecosystems (Govindasamy et al. 2002), ecosystems could continue to be vulnerable due to changes in water resources. In addition, solar radiation management would not address the potentially significant problem of ocean acidification to marine ecosystems.

4.25.3   Adaptation

The majority of both natural and human systems will have to adapt to climate change in some form or the other. A broad array of adaptation strategies has been proposed for reducing the impacts of climate change in both more natural systems and human communities (IPCC 2007a; Heller and Zavaleta 2009) (Table 2). Many of these strategies are either general concepts or strategies that apply to most ecosystems and regions. We begin by describing general concepts and strategies. We then describe some of the strategies that have been proposed for four broad types of ecosystems including freshwater, terrestrial, coastal, and human-dominated systems. For the freshwater, terrestrial, and coastal systems, we focus on strategies that would lessen negative impacts of changing climate on ecosystem functioning and ecosystem services. For the human-dominated systems, we discuss the ways that some of the most often discussed strategies for climate adaptation in these systems will impact (either negatively or positively) ecosystem functioning and the provision of ecosystem services in these and in surrounding areas.

4.25.3.1   General Concepts and Strategies

4.25.3.1.1   Spatial and Temporal Scale
Developing adaptation strategies to address future shifts in climate will require expanding the temporal and spatial scales of plans, policies, and management (Kareiva et al. 2008; Lawler

et al. 2010). Three-year, 5-year, and even 10-year plans will fail to address many climate impacts. Future planning will need to address both short-term and long-term changes in systems. To address long-term changes, plans and policies will need to look at least 20 years into the future and will be more useful if they look ahead 50 or more years for many ecosystems and ecosystem services. It will often also be necessary to expand the spatial scale at which systems are managed and policies and plans are developed. As species move and ecosystems change, it will be necessary to think well beyond neighborhood, park, refuge, state, or even national boundaries. Planning will need to occur at multiple, integrated scales and will need to involve local, regional, and sometimes national participants (Kareiva et al. 2008).

4.25.3.1.2   Environmental Justice

While expanding the temporal and spatial scale of climate adaptation strategies, it will be necessary to keep in view local histories, politics, and economies. Scale and locality also play a formative role for issues of 'environmental' or 'climate' justice. Environmental justice describes the tendency for poor communities to be more vulnerable to environmental degradation. Poor communities tend to bear not only the unequal burden of polluting, destructive, and destabilizing industries but also a disproportionate share of the blame for environmental destruction and responsibility for ameliorating environmental change. For example, polluting industries are often located in poor communities due to cheap land values and the inability of poor communities to politically resist their presence, or a desire to develop jobs at any cost. For instance, swidden agriculturalists in Southeast Asia have been blamed for forest fires despite satellite data pinning large fires to government-sponsored oil palm plantations (Harwell 2000) and Southeast Asian fishers living near toxic riparian runoff from mining have been blamed for polluting local waters by cyanide fishing (Lowe 2006).

4.25.3.1.3   Coordination and Cooperation

The broad spatial scales that are required to address the effects of a changing climate necessitate cooperation and coordination among managers, planners, and policy makers from different jurisdictions, agencies, and management units (Kareiva et al. 2008). They require agencies with diverse mandates and cultures to work together in ways that they have not done in the past. As an example, the US Climate Change Science Program is a federal organization that reaches across federal agencies. The broad scale of climate impacts also requires cooperation across sectors of society and different types of organizations including nongovernmental organizations, local and regional governments, citizen groups, and industry. The US Fish and Wildlife Service's Landscape Conservation Cooperatives are an example of a system designed to bring together diverse groups of scientists, stakeholders, policy makers, and managers to, in part, address climate change. In addition, as emissions from one locale affect the climate in other locales, addressing the global nature of climate change will involve cooperation at an international level (Hannah 2010). Although, as the above examples demonstrate, some regional, national, and international efforts have been put in place to foster collaboration,

more such efforts will need to be made to adequately address climate change.

In addition to cooperation among scientific and political leaders, local and regional stakeholders need to work together as a unified force for social and environmental change. Representatives from the Global North need to appreciate perspectives emanating from the Global South and vice versa. Climate adaptation can be brought into many other environmental and social justice agendas among community advocacy groups and should not remain the purview of the community of knowledge leaders with scientific expertise.

4.25.3.1.4   Resistance, Resilience, and Transition

There are three fundamental approaches to managing systems in a changing climate – promoting resistance, resilience, and transition. Resistance-based adaptation strategies focus on maintaining the current state of a system in the face of climate change or climate-driven changes in the environment. Building a seawall to prevent erosion as sea levels rise and storm surges intensify is an example of a resistance-based adaptation strategy. Resilience can be defined as the ability of a species or system to return to its current state following a perturbation (e.g., Holling 1973). Resilient systems will be able to maintain ecosystem functions and processes and avoid a transition to a new state as climates change. Most of the discussion of climate adaptation to date has focused on managing ecosystems for resistance or resilience. Most of the general adaptation strategies discussed below and the more specific strategies discussed for each of the four types of ecosystems are intended to increase resilience.

The magnitude and rate of projected climatic changes over the coming century will likely make both resistance- and resilience-based strategies insufficient or ineffective in the long run. Managing many systems will require promoting change to a new state. Strategies for promoting change in human-dominated systems may include planting new crops, redesigning road networks, and relocating people. Strategies for fostering change in more natural systems include assisted colonization of threatened plants and animals (see below) and shifting management efforts from one species to another. The outcomes of these more aggressive and forward-looking strategies will be more uncertain, and their implementation will be more controversial. Change is especially hard in social contexts where it is uncomfortable, disadvantageous, expensive, or where the old system is remunerative or beneficial to elites, decision makers, or other small influential groups.

4.25.3.1.5   Adaptive Management

Adaptive management is a flexible approach to managing a system in which the management actions are treated as large-scale experiments (Holling 1978; Walters and Hilborn 1978). It is an iterative process in which the system is monitored following the initial management action and new actions (again treated as experiments) are designed and implemented in response to the results of the initial actions. Adaptive management was conceived for managing highly uncertain systems, and thus it has great potential for managing systems in a changing climate (Arvai et al. 2006). Adaptive management approaches designed to address climate change will likely have four basic steps (Kareiva et al. 2008): (1) assessing the potential impacts of

climate change on the system in question, (2) designing management actions – in the form of experiments with testable hypotheses or predictions – to address the potential impacts, (3) monitoring the system for climatic changes and system responses, and (4) using the results of the monitoring to evaluate the effectiveness of the management actions and redesign them as necessary before repeating the four steps.

4.25.3.1.6 Increasing Diversity and Reducing Threats

It is generally accepted that more diverse systems are more resilient to environmental change than less diverse systems. Thus, restoring or protecting the biological diversity of a system will likely increase resilience of that system to climate change (Glick et al. 2009). This diversity can be in the form of species diversity, environmental diversity, or genetic diversity (Schindler et al. 2010). A second, general approach to increasing resilience of species and systems involves reducing the impacts of other factors that reduce the overall resilience of the species or system. For individual species, this might mean reducing harvest, restoring or protecting habitat, eliminating diseases, or reducing human interactions. For ecosystems, this may mean reducing pollutants, restoring vegetation, reducing human use, and controlling invasive species.

4.25.3.1.7 Assisted Colonization

As climates change, many species need to move to track suitable climatic conditions and changing habitats. In some cases, it may be possible to facilitate movement by increasing connectivity of freshwater and terrestrial landscapes (see Sections 4.25.3.2 Freshwater Systems and 4.25.3.3 Terrestrial Systems). However, many species with limited dispersal abilities or that face significant barriers to dispersal will be unable to respond to changing climates. Assisted colonization is one strategy that has been proposed for facilitating climate-driven range shifts (Hunter 2007; McLachlan et al. 2007); also referred to as managed relocation and assisted migration – assisted colonization is the translocation of species outside their native range to facilitate movement in response to climate change. The concept is controversial for both ethical and ecological reasons. Some researchers have highlighted the potential for negative, ecological, evolutionary, and economic impacts, as well as ethical concerns (Ricciardi and Simberloff 2009; Sax et al. 2009). Advocates argue that assisted colonization will be essential for cases in which species will have to move to find suitable environments but will be unable to do so, that many of the potential risks are overblown, and that guidance can be developed for the strategic and informed use of assisted colonization. Several decision-making frameworks and prioritization strategies for applying assisted colonization have been proposed (Hoegh-Guldberg et al. 2008; Richardson et al. 2009). Although assisted colonization will likely be a useful strategy in many systems, there will be specific factors and risks that will need to be considered for particular systems (e.g., in freshwater systems, Olden et al. 2011).

4.25.3.2 Freshwater Systems

Virtually all freshwater systems are already impacted by human activities (e.g., Vörösmarty et al. 2010). Under current climate projections, virtually all freshwater ecosystems will face significant impacts by the middle of this century. Most of these impacts will be detrimental from the perspective of existing freshwater ecosystems and the human livelihoods and communities that depend upon them (Poff et al. 2002). Discussions have broadly focused on rising water and air temperatures, increasing and decreasing precipitation, increasing evapotranspiration, and changing regimes of groundwater and surface runoff. There are four basic types of adaptation strategies that have been proposed for addressing these impending impacts. We define these as ecological water management, connectivity, protected areas, and restoration strategies. Below, we briefly describe some of the specific strategies that have been proposed in each of these areas.

4.25.3.2.1 Ecological Water Management

Increased water scarcity associated with decreased precipitation and increased warming in some regions is likely to prompt the modification of dams and reservoirs to improve storage capacity (see Section 4.25.3.5.3 Managed Aquatic Systems). Traditional water management has generally sought to dampen the natural variability of river flows to attain steady and dependable water supplies for domestic and industrial uses, irrigation, navigation, and hydropower, and to moderate extreme water conditions such as floods and droughts (Postel and Richter 2003). However, the extraordinary species richness and productivity characteristic of freshwater ecosystems is strongly dependent upon, and attributable to, the natural variability of their hydrologic conditions. Thus, large changes to natural flow regimes can have large impacts on species, ecosystems, and society (Postel and Carpenter 1997; IUCN 2000; WCD 2000).

The water needs of humans and natural ecosystems are commonly viewed as competing. However, water managers and political leaders increasingly recognize that there are limits to the amount of water that can be withdrawn from freshwater systems before their natural functioning and productivity, native species, and the array of goods and services they provide are severely degraded (Richter et al. 2003). This has led to a growing realization that society derives substantial benefits both from out-of-stream extractions of water as well as by maintaining adequate flows of water within freshwater ecosystems. In recent years, the water needs of river ecosystems are receiving increasing attention in water-supply planning, offering hope that many rivers can be protected before their health and ability to provide important goods and services is seriously compromised by water development.

Restoring or protecting some semblance of the natural river flow conditions necessary to support ecosystem function (called environmental flows) into the future is one of the most important climate change adaptation strategies for flowing waters. Recent regulatory mandates and policy decisions calling for restoring and preserving environmental flows have led to a reexamination of dam operations for better protection of river health (Watts et al. 2011). For example, the South African National Water Act (1998) calls for the creation of a reserve of water in each river basin to meet both basic human needs and protect river ecosystem health. Similarly, other national directives and international agreements such as the Water Framework Directive of the European Union are providing mechanisms for river protection, including the provision of adequate environmental flows (Postel and Richter 2003).

Maintenance of environmental flows (flows that sustain river ecosystems) is likely to be the highest priority adaptation response for freshwater ecosystems in most contexts. This will require policies and implementation mechanisms to protect (and, if necessary, restore) flows now, and to continue to provide environmental flow regimes under changing patterns of runoff associated with climate change.

4.25.3.2.2 Connectivity

As air and water temperatures warm, many freshwater species will be forced to rapidly adapt to their new environments, to migrate to more suitable habitats, or face extinction (Heino et al. 2009). Responses of aquatic organisms to climate change will be constrained because they are limited to dispersal along pathways of connected water. Consequently, the linear nature of river systems makes them highly prone to fragmentation from waterfalls, dams, and water withdrawals. Such fragmentation can not only limit dispersal and the ability of species to track climate change but also disrupt the completion of life cycles for many freshwater organisms. For many streams, especially in arid and semiarid ecosystems, there is concern that more frequent and severe droughts will lead to the building of more dams and water diversions, further fragmenting stream networks (Seager et al. 2007).

Increasing the connectivity of freshwater systems is one key way to help aquatic systems adapt to climate change. Species responses to climate change will be limited by human-engineered structures, including hundreds of thousands of dams, diversions, and impassable road culverts that exist globally (Nilsson and Schopfhauser 1995). In the United States alone, there are over 80 000 large dams and an estimated 2.5 million or more small impoundments that disrupt the dispersal of aquatic organisms. In recent decades, however, new water laws and programs have helped to increase habitat connectivity by removing or modifying human barriers to movement in river systems. Increasingly, small dams and diversions are being removed for a number of ecological, social, and economic reasons, including the enhancement of longitudinal connectivity for fish migration (Stanley and Doyle 2003). Similarly, temporary barriers such as impassable culverts under roadways are being modified to allow for easier recolonization and movement of fishes (Roni et al. 2008). Although this management strategy may promote the adaptive capacity of species to respond to climate change, the removal of such obstructions can simultaneously increase the risk of invasion by nonnative species and associated diseases, which are major threats to ecosystem structure and function. In fact, the conversion of culverts into permanent barriers has been a common management approach to protect isolated native populations from invasive species spreading upstream (Fausch et al. 2009). Given the complexities of promoting the movement of native species while concurrently limiting the spread of invasive species, it is unlikely that the removal of barriers to enhance habitat connectivity will be a successful adaptation strategy in all areas for reducing the impacts of climate change on ecosystem function.

4.25.3.2.3 Freshwater Protected Areas

In addition to restoring or protecting environmental flows and increasing connectivity within stream networks, it may be necessary to protect the species themselves to allow them to move through or persist in more intensely managed landscapes. In aquatic ecosystems, this may involve increasing the size of existing reserves or creating new protected areas that encompass important freshwater resources and allow for native species and assemblages to persist into the future (Abell et al. 2007). Such acquisitions and agreements ideally would capture a large portion of the geographical, ecological, and geophysical range of multiple species, thus increasing opportunities for organisms to adapt and evolve to changing environmental conditions. Protected areas have historically been a cornerstone of terrestrial conservation – and are discussed in much more detail in that section, below. Nonetheless, protected areas will likely play a major role in protecting aquatic species as climate change and areas could easily be prioritized to provide protection for both terrestrial and aquatic systems in a changing climate (Abell et al. 2007).

4.25.3.2.4 Restoration of Riparian Vegetation

Projected increases in air temperatures, combined with reduced snowpack, earlier onset of spring peak flows, and lower summer baseflows, will have direct implications for the thermal regimes of streams and rivers (Poff et al. 2002). The ecological implications of stream warming are significant. Water temperature directly influences the metabolic rates, physiology, and life histories of aquatic species and helps determine rates of important ecological processes such as nutrient cycling and productivity. In general, warming will produce a general shift in species distribution poleward with extinctions and extirpations of cold-water species at lower latitudes and range expansion of warm-water (often invasive species) and cool-water species into higher latitudes.

Restoring and protecting riparian vegetation – the trees and shrubs that grow along the banks of rivers and streams – has the potential to reduce stream temperatures in certain places. Recent modeling suggests that riparian habitat restoration can play an important role in offsetting the effects of climate change. Battin et al. (2007) used a series of linked models of climate, land cover, hydrology, and salmon population dynamics to investigate the impacts of altered stream flow and temperature on the effectiveness of proposed habitat restoration efforts designed to recover Chinook salmon populations in the Pacific Northwest of the United States. This study showed that in the absence of habitat restoration, basin-wide spawning populations would decline by an average of 20–40% by 2050. By contrast, they found large increases in juvenile rearing capacity associated with proposed riparian habitat restoration, which limited climate-induced declines to 5% according to one climate model and increased salmon abundance by 19% according to another model. However, the model results showed that not all expected climate impacts could be mitigated entirely. In relatively narrow streams, reforestation was predicted to decrease water temperatures by increasing shading, but in wide, main-stem reaches where most Chinook salmon spawn, riparian vegetation had a minor effect on water temperature. In addition to restoring riparian areas, targeted protection of forested riparian buffers using fencing to stop livestock from entering the stream and trampling/grazing vegetation or conservation easements to eliminate farming activities may also help to reduce stream temperatures.

4.25.3.3   Terrestrial Systems

The many adaptation strategies that have been proposed for addressing climate change in terrestrial systems can be loosely grouped into three categories – those that involve protected lands and conservation planning, those that address connectivity, and those that are more species or site specific in nature.

4.25.3.3.1   Protected Lands and Conservation Planning

Protecting land is arguably one of the most effective ways of conserving biodiversity and terrestrial ecosystem services. It is generally assumed that lands that are selected to protect today's species and ecological systems will protect those species and systems into the future. Climate change brings this assumption into question. As climates change and species distributions shift, species will move into and out of reserves. Changes in species composition, the timing of ecological events, and the rates of ecosystem processes will result in changes in the functioning of ecosystems and the services they provide. Many proposed adaptation strategies address these challenges by augmenting current protected areas with additional reserves, parks, and preserves (Heller and Zavaleta 2009; Lawler 2009). These strategies range from broad calls for more protected lands to more sophisticated recommendations about how to select new lands or design new reserves to better protect biodiversity and ecosystem services as climates change.

A number of strategies have been proposed for determining where to put new protected lands to best address the effects of climate change. Some of the simplest strategies involve placing reserves at the poleward or elevational boundaries of the range limits of specific species (Peters and Darling 1985), at major transitions between vegetation formations (Halpin 1997), or at the core of species environmental distributions (Araújo et al. 2004). Others have proposed placing reserves between existing reserves – in the hopes that those new reserves will act as stepping stones allowing species to better move from reserve to reserve. Yet another recommendation involves placing reserves across strong environmental gradients. Reserves that span many different environments will potentially allow species to shift their distributions without leaving the reserve.

In addition to these simple rules of thumb for placing reserves to address climate change, many more sophisticated approaches to selecting areas for new reserves have been proposed. For example, modeled climate-driven shifts in species distributions can be used to select new reserves that will protect biodiversity today and into the future (Hannah et al. 2007; Vos et al. 2008; Hole et al. 2009). Although this approach may prove useful for some species and systems, care must be taken in the use of the models developed to project species range shifts. There are many uncertainties associated with the models themselves and the climate projections on which they rely. Another proposed approach to building a reserve network that will be resilient to climate change involves protecting environments in lieu of protecting species and systems. This approach has been referred to as 'protecting the ecological stage.' This analogy implies that the species and the ecological systems are players and that the soils and topography of a region form the stage on which they interact and evolve. By protecting a suite of diverse environments, it is assumed that one will protect the areas where new ecological

systems can develop as climates change (Anderson and Ferree 2010; Beier and Brost 2010). Similarly, others have suggested that more resilient reserve networks will be those that include a diversity of current climates (Pyke and Fischer 2005). Although climates will change, many of the climate gradients generated by latitudinal and topographic patterns will remain. Thus, a set of reserves that protects a diversity of climates today will likely protect a diversity of climates in the future. At least one recent study has applied the concept of protecting environments (topographies, soils, and climate gradients) to a reserve-selection problem (Schloss et al. 2011). One last approach to building a resilient reserve network in a changing climate involves placing reserves in areas that are likely to serve as climate refugia. Refugia are areas that are projected to experience minimal climatic changes and/or have cooler microclimates (Saxon et al. 2005; Hansen et al. 2010; Shoo et al. 2011).

One potential opportunity for climate change adaptation is to consider people as an essential component of species conservation and climate adaptation. While reserve and park systems have a long history of alienating local people, using violence and other coercive measures to separate people and wildlife, in this case, local livelihoods are also threatened by climate change. This provides an opening for a new approach to conservation and a new discourse on the relationship between local people and wildlife.

4.25.3.3.2   Connectivity

As for freshwater systems, improving the connectivity of the terrestrial landscape will be critical for addressing climate change. In response to historical climatic changes, many species shifted their ranges – moving toward the equator as ice sheets advanced and moving poleward as the ice sheets retreated. Today's species will have a much harder time responding to current and impending climatic changes. Present-day landscapes – unlike the landscapes of the distant past – are fragmented by roads, agricultural fields, and residential development. Given that many species will have trouble moving across these human-dominated landscapes, it will be essential to reconnect fragmented landscapes to allow species to respond to shifting climates. Not surprisingly, improving landscape connectivity was the most often recommended climate change adaptation strategy in a recent review of the literature (Heller and Zavaleta 2009).

Many of the recommendations for increasing connectivity involve designing corridors that connect current protected lands. Traditionally, such corridors have been designed for particular focal species, and they have connected reserves or remaining fragments of habitat. However, corridors that facilitate species ranges shifts and the reshuffling of ecosystems will need to connect what is habitat for a species today with an area that may become habitat in the future. In this way, corridor design will need to evolve to address climate change. One such approach to developing corridors for addressing climate change involves basing the corridors on environmental gradients instead of on the current vegetation (which is often used as a measure of habitat) (Beier and Brost 2010). Another approach uses projected changes in climate to orient corridors (Ackerly et al. 2010). A third method involves using modeled shifts in species distributions to identify potential routes that

species would need to take to move from currently suitable climates to places where climates will likely be suitable in the future (Williams et al. 2005; Rose and Burton 2009). These three approaches are based on different assumptions and have different levels of associated uncertainty. In general, the uncertainty increases with the intensity of modeling required to identify the corridor, and thus the first of the three approaches has the least inherent uncertainty and the last of the three has the most.

Although corridors may be useful for some species, they will not be feasible or effective in all places or for all species. In addition to designing corridors to facilitate species movements, it will likely be necessary to improve the permeability of the landscape in general (Franklin and Lindenmayer 2009). Increasing landscape permeability will involve changing the way we use and manage the landscape. Changes in forest harvest practices from clear-cuts to selective, retention harvests can increase the connectivity of forested landscapes. Landscape planning and zoning for residential development can reduce landscape fragmentation. Windbreaks, fencerows, and crop choices can be used to increase the connectivity of agricultural lands. At a finer scale, choices of landscaping plants, road placement, and wildlife over- and underpasses can increase landscape permeability.

4.25.3.3.3   Species- and Ecosystem-Specific Strategies
Protected lands and connectivity increase species ability to adapt to changing climates at relatively large spatial scales. In general, they address species movements. Adaptation strategies are also needed at finer scales. In particular, strategies are needed that address individual species and ecosystems. Many of these finer scale approaches tend to involve reducing temperatures or otherwise offsetting the exposure to the changes in climate or climate-driven changes in environmental conditions. For example, it may be possible to reduce temperatures by restoring vegetation to provide shade (Wilby et al. 1998; Wilby and Perry 2006). It may be possible to reduce the impacts of changing fire regimes through forest management practices. Fire suppression policies, may, for example, have particularly severe ramifications in a climate in which fires will generally be larger and more frequent. It may also be feasible to provide supplemental water for particularly vulnerable plants or animals in times of drought or during heat waves. Similarly, shade shelters could be provided to help some animals weather heat waves in extreme climates. Although some of these strategies may prove useful in the short term, many will be neither cost-effective nor long-term solutions.

Another system-specific approach to addressing climate change involves altering species composition or community structure in a way that allows a system to better cope with climatic changes. For a forested system, this may mean planting new species or planting seeds of the same species that have a different genetic makeup (Millar et al. 2007; Glick et al. 2009). Likewise, for grasslands and shrublands, this may mean choosing different species or strains for restoration purposes. Moreover, it may mean facilitating the transformation of an ecosystem – for example from a shrubland to a woodland or from a shrubland to a grassland. In many cases, the first species to move into these transitioning systems may be invasive species. Facilitating the transition to a new state using species

native to the region may, in many cases be preferable to having new systems dominated by invasive species. These extreme cases will require ex situ conservation strategies, including seed banking and captive breeding to ensure the long-term survival of the species.

4.25.3.4   Coastal Systems
The interface between the land, sea, and air found in coastal areas is a high-energy system subject to storms, winds, and tides. It is also where the majority of protein comes from in many regions of the world. Many vital ecosystem services are provided along coastal margins of continents and islands. Fringing coral reefs and mangrove forests buffer wave energy, which reduces erosion along the coast. These systems also provide critical habitat for many species, especially nursery areas for provisional services such as fisheries. In many areas, sea-level rise and associated storm surges will make it difficult to protect these systems and the services they provide. Nonetheless, there are two main approaches that will likely prove most useful in coastal systems: building resilience through protection and restoration and facilitating the transition to new ecosystems.

4.25.3.4.1   Protection and Restoration
One of the more beneficial ways, from both an environmental and economic standpoint, to adapt to predicted changes from climate change is by protecting and restoring natural systems that provide multiple ecosystems services. This would include protection of human infrastructure from sea-level rise and increased inundation. Protection and restoration of natural buffers such as barrier islands, mangroves, and coral reefs not only require little financial construction and maintenance but also maintain the wealth of ecosystem services associated with these systems, which include nursery and rearing habitat for many commercial seafood stocks such as fish and shrimp, recreational and cultural opportunities for humans, and protection from inundation. Some natural protection features such as sea ice cannot be maintained in the face of increasing temperatures. In Alaska, the loss of sea ice and melting of permafrost due to warming ocean and air temperatures has exposed the shore to wave energy that used to be absorbed or damped by sea ice or frozen soils. Undoubtedly, ecosystem services that depended on that sea ice protection have also been lost.

Many regions have seen a huge decrease in the area covered by mangroves as coastal areas are drained and mangroves removed for aquaculture. Worldwide, it is estimated that more than 50% of mangrove forests have been destroyed or converted to other uses. On a local scale, many areas have lost all of their mangroves. This loss destroys a wide range of ecosystem services provided by these forests, which range from carbon sequestration to flood protection, spawning, and rearing grounds for many fish and other marine species. Restoring mangrove forests results in increased storm surge protection for natural and human coastal systems, provides nursery habitat for many commercially important fisheries, and stores sediments that may damage offshore coral reefs.

Worldwide, corals exhibit well-documented environmental adaptability over time scales of weeks to thousands of years.

Corals are actually two creatures that live together in a symbiotic relationship. Zooxanthellae are the algal component of corals that provide nutrients generated from photosynthesis to the animal component. Different zooxanthellae species and different species of corals in general have differential environmental tolerances. For example, some corals near the Arabian Peninsula exist under conditions of salinity and temperature that are greater than near-term predicted future average salinities and temperatures resulting from climate change. These adaptive changes likely operate on a decadal time scale. Thus, in some cases, it may be possible to identify particular species or zooxanthellae and algal combinations that are more resilient to warming. Protecting coral reefs from other stressors such as excess sediment and/or nutrient and pollutant inputs from terrestrial sources and unregulated diving can increase the coral's ability to adapt to increased water temperatures. Technological adaptation measures include using sprinklers to create roughened sea surface to decrease light penetration or covering reefs with shade cloth to limit bleaching of corals.

4.25.3.4.2   Transition and Migration

As sea levels rise, many coastal systems will need to migrate inland. When there are extensive human uses of coastal space or urban buildup, space for ecosystem recovery and migration of species will not be available. Providing space for the migration of biotic elements of the coastal system at the same time as when human populations are forced to move would provide cobenefits for coastal life and human communities. Ecosystems will usually adjust to changing salinities and water levels, and the services provided by the system will be maintained where conditions are suitable. For example, in 1996, a subdivision east of Houston in Baytown, Texas, was bought out, the structures removed, and the entire area restored to coastal wetlands. A more extreme example of planned retreat is the Maldive Islands. Their current plan is to exploit the current coastal amenities, primarily beaches and coral reefs; secure capital with which to train younger citizens; and prepare them for relocation to other countries such as India, Sri Lanka, and Australia. In the short term, there are negative consequences to ecosystem services due to commercial and touristic exploitation, but in the long run, by abandoning the islands, the system will be able to come to a new ecological state.

In some cases, removing human infrastructure will be a necessary but insufficient means of fostering landward shifts in coastal systems. In such cases, it may be necessary to facilitate the shift in natural systems and stabilize soils by planting more coastal species inland as water levels rise. Such actions have been taken as part of the Alligator River climate change adaptation project on the North Carolina coast in the southeastern United States (Pearsall 2005, Pearsall and Poulter 2005).

4.25.3.5   Human-Dominated Systems

Here we describe some of the adaptation strategies that have been proposed for built environments, agricultural systems, and managed freshwater systems. We explicitly focus on how the most commonly proposed strategies could affect associated ecosystems.

4.25.3.5.1   Built Environments

The severity of climate change impacts will depend, in large part, on our ability to transform the built environment in response to changing conditions. The following section discusses some of the climate change adaptation strategies that will likely take place in built environments and the effects that these strategies may have on ecosystem functions and services. We briefly discuss human migrations, flood control, sea-level rise, increased water storage, and urban heat-island effects.

Perhaps the most basic form of climate change adaptation involving the built environment is human migration. Vulnerable populations will be forced to abandon their homes, relocate, and rebuild. They will displace resident populations and open up the possibility of conflict in the process. The bulk of climate change-related human migration that is already occurring involves movement from rural areas to cities in developing countries. Unplanned urban growth will fuel the expansion of informal urban settlements, and by 2050, 3×10^9 people, one-third of the world's population, may inhabit urban slums. In both rural and urban environments, proactive planning and resettlement strategies that identify populations at risk and relocate them stand to drastically reduce long-term human hardship stemming from climate change. They can also protect vital ecosystems from the degradation associated with unplanned development. However, resettlement can have profound negative impacts. Poorly executed, it can degrade indigenous culture, undermine traditional livelihoods, destroy social networks, and deepen poverty by distancing poor communities from employment opportunities. Given these dangers, in some cases, it is preferable to fortify communities against climate change impacts in place. This approach introduces improvements to infrastructure and housing, builds upon the prior efforts of communities, and preserves social networks.

In many regions, climate change will result in increased rainfall and flooding. Conventional approaches to storm water management rely on defensive hard structures. Water runs from impermeable concrete and asphalt surfaces into storm drains, culverts, and concrete embankments. Rivers are straightened, channelized, and isolated from their natural floodplains to accommodate human settlement. As flood events become more intense and frequent with climate change, storm water management strategies must evolve. Rather than take a defensive stance, they should promote the coexistence of humans, habitat, and water. Soft infrastructure or low-impact development strategies, such as permeable paving, green roofs, green walls, rain gardens, bioswales, and constructed wetlands offer a promising alternative to conventional storm water infrastructure. They promote groundwater recharge, reduce flooding, and improve water quality with downstream benefits to aquatic habitats. In areas of severe flood risk, resettling residents on higher ground and reintroducing rivers to their floodplains protects human populations, dissipates flood energy, and creates wetland habitat. Through temporal land-use practices such as intermittent farming, floods become an asset rather than a threat, depositing sediments that enrich agricultural lands.

By 2050, rising sea levels may displace as many as 162 million people (Myers 2002). Like conventional storm water infrastructure, conventional seawall infrastructure relies

on defensive hard structures. As sea levels rise, existing levees will become obsolete. Here again, soft-infrastructure strategies offer a promising alternative. Graduated transitions from sea to land including manmade offshore islands, expansive shallows, and coastal marshes act as buffers for storm surge better equipped to absorb the impacts of extreme weather events. They provide habitat for marine species and, in coastal cities, public space for recreation when conditions permit.

In places like coastal Peru and sub-Saharan Africa, disappearing glaciers and reduced precipitation will increase the frequency, duration, and impacts of drought, undermining food and water security. A number of interventions in the built environment can help communities cope with water scarcity. Increasing water storage at scales ranging from dams to urban reservoirs and household rainwater barrels helps bolster water supplies during prolonged dry periods. In coastal areas, desalination plants and, in select localities of South America and Africa, fog harvesting may prove to be viable alternative water sources. Ecological sanitation technologies such as dry toilets and gray water wetlands conserve potable water for drinking and, as part of a network of integrated ecological infrastructure systems, irrigate and provide nutrients for urban farms and forests. They also help prevent contamination of local water bodies, preserving their viability as sources of potable water and ecological integrity. Further impacts of, and opportunities associated with, these various adaptation strategies are discussed in the Sections 4.25.3.5.2 and 4.25.3.5.3.

Cities in developed countries are on average 1–3 °C hotter than the surrounding countryside (UN Human Settlements Programme 2011). Higher urban temperatures increase energy use, degrade urban air quality, raise the temperature of urban storm water runoff, and contribute to general discomfort, respiratory illnesses, heat stroke, and other heat-related illnesses. Warming in conjunction with increased urbanization will amplify urban heat-island effects and their associated impacts.

Several strategies can help reduce urban temperatures. At the scale of the site, urban trees with high, dense canopies, strategically planted around buildings, in parking lots, and along streets permit the passage of air, shade heat-absorbing surfaces, and cool the atmosphere through evapotranspiration. They also reduce the temperature of runoff water. Green roofs perform a similar function on roof surfaces. Buildings and landscapes constructed from materials with high solar reflectance or albedo absorb less heat and reduce urban temperatures. At a larger scale, streets oriented parallel (or up to 30°) to prevailing winds, permeable networks of public open space, strategically situated low-rise buildings, and gaps between high-rise structures increase the air permeability of urban environments.

4.25.3.5.2   Agricultural Systems

Increased temperatures and changes in precipitation regimes are likely to have negative impacts on global food security by worsening the existing regional disparities between developing and developed countries (Easterling et al. 2007; Rosenzweig and Tubiello 2007). This is supported by the prediction that a moderate warming accompanied with elevated CO_2 concentrations is likely to lead to an increase in crop productivity of developed countries in temperate mid and high latitudes, whereas even a slight increase in temperature could damage crops that are already growing at supraoptimal temperatures in countries located in tropical, low latitudes (Easterling et al. 2007; Easterling 2010). As in other systems, even with significant mitigation efforts, adaptation strategies will be necessary to address the impacts of climate change on agriculture.

Adaptation strategies for more resilient agricultural systems may include altering the timing and location of cropping, switching crop species and cultivars, selecting livestock breeds, crop rotations, and efficiently using and managing water resources. These types of adaptation strategies have been referred to as autonomous strategies (Easterling 2010). Implementing some of these strategies, such as changing the type of livestock that is grazed or changing crop rotations could have profound effects on ecosystem functioning. However, in general, these types of adaptation strategies will have environmental impacts smaller than more intensive strategies that are designed to transform systems.

For many agricultural systems, the magnitude of climatic changes will necessitate more intensive planned adaptation strategies that foster significant transformations of systems or infrastructures (Easterling 2010). Such intensive strategies will be particularly important for sub-Saharan Africa and South Asia where climate will have major impacts on agriculture (Lobell et al. 2008; Nelson et al. 2009). These planned adaptation options include developing new infrastructure (e.g., irrigation infrastructure, transport and storage infrastructure, and efficient water use and reuse technologies), investing in new technical and management options (e.g., crop and livestock improvement, enhancing germplasm), shifts in the distribution of agriculture (e.g., abandoning some areas and farming new lands), and building the capacity to make continuing adjustments. Here, we discuss two of these strategies – improving crop performance and water conservation – in more detail.

Stresses on crops due to extreme heat and pest and pathogen pressures are likely to increase with climate change (Deutsch et al. 2008; Battisti and Naylor 2009). Multiple adaptation options are available for improving crop performance in the face of such climate-driven stresses. First, in conjunction with conventional breeding, crop improvement through genetic engineering is seen as an effective adaptation tool in a changing climate – although public opinion is often divided on the use and consequences of genetically engineered crops (MacDiarmid 2007; Jones 2011). A second approach involves maintaining crop genetic diversity by, for example, collecting and storing the diversity of current cultivars or local landraces. A third adaptation strategy involves exploiting symbiotic relationships between crops and other organisms. For example, it has been shown that numerous fungal and bacterial endophytes confer stress tolerance to heat, drought, salinity, and pathogen attacks (Rodriguez et al. 2008; Rodriguez et al. 2009), and others promote growth and fix atmospheric nitrogen (Doty et al. 2009; Xin et al. 2009). Other strategies include the application of kaolin particle films to reduce heat stress and photoinhibition and to mitigate pest damage (Glenn et al. 1999; Glenn 2009) as well as the incorporation of biochar into soils to confer numerous agronomic benefits that enhance crop performance and stress tolerance (Marris 2006).

Irrigated agriculture accounts for about 70% of the world's freshwater withdrawals (Rosegrant et al. 2009). With increasing global population, the demand for irrigated agriculture will continue to increase globally because realized crop yields normally increase considerably with irrigation. Adaptation strategies that foster more efficient use of water in agriculture will be critical for achieving global food security while conserving water in a changing climate. These strategies will include institutional water management reform, economic incentives for efficient water use, and infrastructure investment for efficient irrigation and water delivery systems (Rosegrant et al. 2009). The 'virtual water' trade through crop products from water-abundant to water-deficit areas should be considered as one of the key adaptation options to climate change (Rosegrant et al. 2009; Easterling 2010). Improving crops for higher water-use efficiency (i.e., greater yield with less water use) should be a goal for genetic, ecological, and agronomic options of adaptation discussed above. Alternative strategies of increasing water storage capacity with dams and increasing the number of stream diversions for agriculture will, in contrast, have significant impacts on aquatic ecosystems (see the Section 4.25.3.5.3 Managed Aquatic Systems).

4.25.3.5.3   Managed Aquatic Systems

As discussed above, changes in temperature and precipitation are likely to lead to changes in the demand for water. Projected climatic changes will likely lead to increased demands for residential use, irrigated agriculture, hydropower production, and carbon capture and storage technologies. In some regions, current water management may not adequately cope with the impacts of changing precipitation regimes and increased evaporation on the reliability of water supply, flood risk, health, agriculture, energy generation, and freshwater ecosystems (Palmer 2008). Adaptation strategies designed to address water management for human uses will either directly or indirectly affect ecosystem functioning and ecosystem services. In addition to the adaptation strategies for addressing water demands for agriculture and residential use (addressed to some extent in Sections 4.25.3.5.1 and 4.25.3.5.2), other important adaptation strategies for managed aquatic systems that will impact ecosystem functions and services include increased extraction of groundwater, improving storage capacity by building or modifying dams and reservoirs, desalination of seawater, and expansion of rainwater storage and water transfer (Bates et al. 2008; Hirji and Davis 2009).

Improving storage capacity by building or modifying dams and reservoirs is likely to be one of the most common regional responses to decreased water availability and increased demand for water. The great utility of running water has resulted in the extensive exploitation of streams and rivers by humans throughout the world, a process greatly facilitated by the construction of hundreds of thousands of dams globally (Nilsson et al. 2005). By capturing high river flows and releasing the water in a carefully controlled manner, dam managers can deliver steady and dependable water supplies to downstream areas, protect settlements from floods, or generate power. Although human manipulation of the world's river flows has provided many societal benefits, it has also caused considerable ecological damage and the loss of important ecosystem services valued by society (Baron et al. 2002). Flow

regulation for hydropower and storage, diversion for human use, and extraction of groundwater connected to stream systems often significantly affect the natural seasonal and interannual variation in river flow, commonly referred to as the natural flow regime (Poff et al. 1997). A natural flow regime is needed to sustain the complex riverine and riparian ecological functions and processes that support native biodiversity and provide myriad ecological services including maintaining water quality, recharging groundwater, and nutrient cycling (Naiman et al. 2002).

Facing an ominous future of increasingly severe water-supply shortages in many areas of the world, social planners and government leaders are exploring strategies for ensuring that enough water of sufficient quality is available for use by future generations. Human demands for water are expected to increase under a warmer climate, exacerbating current management problems. Increasing demands for irrigation and industrial cooling water could conflict with the increasing demands for municipal water supplies resulting from urban growth. Climate-induced changes to water availability and increasing human demand for water are likely to prompt the construction or modification of dams and reservoirs to improve storage capacity and enhance water security (WCD 2000; Palmer 2008). For instance, by storing water in reservoirs, water managers capture high flows during wet years or seasons to supplement water supplies at drier times, thereby maximizing the reliability of water supplies and certain economic benefits each year. For regions where increases in runoff variability or more prolonged drought conditions are associated with climate change, the pressure to build water-supply reservoirs will be great.

Although the construction of additional dams and reservoirs will undoubtedly provide many societal benefits, a rich body of scientific knowledge has shown that river regulation also causes considerable ecological damage and the loss of important ecosystem services valued by society (Baron et al. 2002; Postel and Richter 2003). River ecosystem health deteriorates when natural flows of water, sediments, and organic materials through a river system are substantially disrupted or modified by human activities (Poff et al. 1997; Richter et al. 2003). River damming and associated environmental alteration is now widely recognized as a leading cause of declines in freshwater biodiversity globally (Bunn and Arthington 2002). Dams have also been implicated in the loss of commercial fisheries in many estuaries and coastal areas, and in the degradation of other natural ecosystem products and services worldwide (WCD 2000). In addition, reservoirs increase the loss of water due to evaporation. Finally, as mentioned above, reservoirs emit substantial quantities of carbon dioxide and methane into the atmosphere (St. Louis et al. 2000), and therefore, the creation of additional reservoirs is likely to further promote climate change.

In many regions, impending water shortages will also lead to greater interest in desalination as a technique for tapping into the vast and infinitely tempting water supplies of the sea. Recent improvements in reverse osmosis technology, coupled with the rising cost and increasing unreliability of traditional water supplies both currently and projected in the future, are making desalination a water-supply option with major plants in operation, in planning, or under consideration in Europe,

North Africa, North America, Australia, China, and India. Like most large-scale industrial processes, making water has a number of actual or potential impacts on aquatic goods and services (WWF 2007). Emerging issues include significant cost and pollution emitted by desalination plants and the mostly unknown, but potentially substantially, effects on freshwater and coastal ecosystems. Intake pipes can remove larvae and small marine organisms, and discharge from desalination plants can elevate levels of salt and other constituents of seawater such as boron; dead sea life, which consumes oxygen while decomposing; chemicals added to change the composition of the water for processing, as well as reducing contamination and clogging of filters and membranes; corrosion by-products; and the heat added for or during processing. Finally, water manufacturing is an energy-intensive process.

4.25.4   Social Considerations in Planning for Mitigation and Adaptation to Climate Change

Although increasing GHG concentrations and the resulting increasing temperatures are global phenomena, the globe will often be an inappropriate scale for developing mitigation and adaptation strategies. Human activities generate differential risks and vulnerabilities that vary with location due to differences in social, political, cultural, and economic conditions (Beck 1992). Although, in one sense, all people are vulnerable to catastrophic climate change, at another more fundamental level, the risk of climate change impacts (along with blame and responsibility) are unevenly distributed. We can begin to think of the unequal distribution of the vulnerability to climate change as a scale issue.

Mitigation and adaptation strategies can be applied at multiple, and often overlapping, scales. At the finest scale, the development of mitigation strategies will depend on local leadership and the attitudes of local populations and individuals toward climate change. At national and international levels, mitigation efforts will be organized through large and formal programs and institutions (e.g., UN-REDD). Although some adaptation strategies will be national and international in nature, much adaptation will take place at finer scales of communities and regions. A hallmark of climate change as a global phenomenon is that leadership and coordination across local, national, and international scales is important for ameliorating its effects. In turn, coordination across scales will entail understanding local climate risks and local and regional understandings of the causes of climate change and the costs and benefits of different mitigation and adaptation strategies.

The effectiveness of any mitigation or adaptation strategy (building codes, population planning, dietary changes, etc.) depends on its acceptance in local, regional, and national communities. Social impediments to adoption of climate change strategies include ideological outlooks, structural constraints, and cultural barriers. For example, free-market ideologies can impede the ability of governments to invest in alternative energies; agricultural subsidies and corporate monopolies on agricultural inputs may create structural barriers to alternative agriculture; and cultural norms for relative water and energy use, family size, or the flavor and texture of food can inhibit conservation of resources and changes in diet.

There is a clear disparity between societies that have contributed the most to GHG emissions and those that will likely suffer the direst consequences of climate change. At the international level, efforts to shift blame from the activities of the rich to the actions of the poor have been used to shirk the responsibility to mitigate climate change and to impede the development of global mitigation strategies. The dispute between the Global North and South over who caused climate change and who must now take responsibility for mitigation is by now well known. Countries in the Global South argue that northern countries have already developed their economies relying on fossil fuel consumption and now, when it is their turn to develop, they are asked to put restrictions on their energy consumption and natural resource use. Meanwhile, the United States has used the reluctance of developing countries to cap emissions as an excuse for inaction on its part. Mitigation and adaptation activities that do not take globally inequalities in wealth, resources, and adaptive capacity into account, or insist on 'equality' in action in a demonstrably unequal world cannot be effective.

Addressing population growth clearly plays a key role in both mitigation and adaptation strategies. However, focusing on population size while ignoring global patterns in the consumption of resources and the distribution of wealth will result in failed policies and strategies. The world's human population is approaching 7×10^9, and a growing population inevitably means greater demand for the numerous goods and services supported by terrestrial and aquatic ecosystems. While the availability of resources has seemingly stretched beyond the direst predictions of several decades ago, the crisis of over-consumption – namely, of coal and other fossil fuels that produce GHGs and contribute to climate change – is simultaneously becoming clearer. While trends over the past several decades suggest that population growth is a significant driver of CO_2 emissions (Bongaarts 1992; Dietz and Rosa 1997), it is also true that urbanization, aging, and changes in household size similarly affect energy use and emissions (MacKeller et al. 1995; Cole and Neumayer 2004). Particular point sources of GHG emissions from energy consumption in developed countries, like the internationally managed oil fields of Nigeria or emissions from the recent Iraq war, which since 2003 has released over 140 million metric tons of carbon dioxide, the equivalent of adding 25 million new cars to American roads (Reisch and Kretzmann 2008), should bear at least as much scrutiny as the desires of third world women and men to bear children. An overarching emphasis on population detracts from a nuanced understanding of the multiple drivers of GHG emissions.

It will be ineffective to focus on the effects of climate change on ecosystems without considering the concurrent effects on human well-being and vice versa. Disparities in climate change risk and human health often overlap, and human health and environmental health are intricately intertwined. Although diseases are often approached as singular phenomena, good models exist that demonstrate the interactive effects of multiple morbidity factors on health outcomes and disease trajectories. For example, interactions between acquired immune deficiency syndrome and tuberculosis, or diabetes and severe acute respiratory syndrome, have synergistic impacts on patients that must be understood together. Likewise, social attributes, like

poverty or exposure to racism, interact with disease conditions to increase the damaging effects of disease. Such interactions have the potential to influence the effects of climate change on disease movement and clustering, disease interactions, and the impact of climate change on global health (Baer and Singer 2008). Human action and human vulnerability to such interactions between climate, disease, and the environment are structured by social and economic inequality, and thus mitigation and adaptation strategies will need to take these inequalities into account.

What is clear from a social and political perspective on mitigation and adaptation is that no one set of mitigation or adaptation strategies will be applicable to all people in all places. Suggested approaches to either mitigation or adaptation will involve costs and benefits that are unequally distributed across nations, populations, and societies. There will, for example, always be those who can escape pollution with air filters and private vehicles, use air conditioning to survive heat waves, have access to global food markets and multiple water sources, and those who cannot. The most effective mitigation and adaptation strategies, therefore, will address both climate change and environmental justice.

Acknowledgments

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