CHAPTER 29

ECOSYSTEM SERVICES

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KEY CONCEPTS

- **Ecosystem services are the benefits that nature provides to people.**
- **Many of the services that nature provides are linked either directly or indirectly to human health outcomes.**
- **These ecosystem services are likely to be severely affected by climate change, with multiple health consequences.**

What Are Ecosystem Services?

People living in many tropical regions collect wood and shellfish from mangrove forests. These same mangroves are fish nurseries helping to support local and global fisheries. The forests accumulate and sequester carbon helping to reduce climate change. The trunks and roots of these trees slow down storm winds and waves protecting coastal communities from storm impacts. These benefits are examples of **ecosystem services**: the benefits that nature provides to people. Mangroves can also provide dis-services, such as mosquitos that can be a nuisance to people and carry disease.

There are three types of ecosystem services: provisioning, regulating, and cultural (Millennium Ecosystem Assessment 2005; Carpenter et al. 2009; Potts et al. 2016). **Provisioning services** are the most familiar, including crops, fish, timber, and drinking water. Most **provisioning services** are bought and sold in markets and have a market value. **Regulating services** are less apparent but often immensely important to people. These include the filtration and purification of water by wetlands or shellfish and the regulation of erosion of sediments that can support and build productive coastal deltas but also fill up hydropower, irrigation, drinking, and flood control reservoirs. Ecosystems such as wetlands regulate water flows in ways that buffer and reduce flooding frequency and intensity. Coastal habitats such as marshes, mangroves, or coral reefs can reduce wave energy, protecting shorelines from erosion, which, in some cases, offers significant protection to property and people. **Regulating services** also benefit agricultural areas by providing habitat for pollinator species (such as bees) or pest control species (such as birds). **Cultural services** include the opportunity for outdoor recreational or cultural activities, such as boating, swimming, hiking, hunting, and fishing, which can provide substantial economic value in many places (U.S. Bureau of Economic Analysis 2019). Other cultural services are more difficult to quantify but can be very important to people. These include the beauty and aesthetics of natural or partly natural areas (e.g., lakes, forests, pastoral landscapes), the sense of peace and release of stress associated with being in a natural setting, the satisfaction from being able to choose a way of life that depends on natural resources (e.g., fishing, farming), and spiritual or cultural connection to a place that is important to many people including Indigenous peoples.

Although our dependence on ecosystem services may not be obvious in daily life, humans simply could not live on this planet without them. This stark reality was demonstrated in 1991 when eight scientists were sealed into a miniature earth system, called Biosphere 2. It was designed with a rainforest, a grassland, a desert, fresh and saltwater wetlands with mangrove trees, and a coral reef in a miniature ocean to inform the future of life support systems for long-term space travel

(Nelson 2018). Amazingly, the scientists were able to produce sufficient food without synthetic fertilizers or pesticides, but they faced many problems with rampant growth of cockroaches, ants, algae, and morning glories, as well as the overproduction of carbon dioxide and underproduction of oxygen from their plants. This experiment clarified how many benefits nature provides to our daily life and how much we still have to learn about how to manage them. Ecosystem services are provided by natural systems in a delicate balance, and effects of climate change have the potential to drastically alter or disrupt these services.

How Does Climate Change Affect Ecosystem Services that Have an Impact on Human Health?

In this section, we describe how various ecosystem services affect human health and then discuss how climate change might disrupt or alter the delivery of these services.

Provisioning Services

Food (Crops, Livestock and Seafood)

Nature can be directly linked to human health through provisioning services. Clearly, human food and nutrition security are tightly tied to ecosystems' provision of healthy crops and fisheries. Globally, approximately 82 percent of the calories in the human food supply are provided by terrestrial plants (mostly cultivated crops), 16 percent by terrestrial animals (mostly cultivated livestock), and 1 percent by aquatic animals and plants (Food and Agriculture Organization [FAO] 2019). Capture fisheries and aquaculture together provide 17 percent of animal protein consumed by the global population and micronutrients in seafood can lower risk of cardiovascular disease; improve maternal health and pregnancy outcomes and increase early childhood physical and cognitive development; improve immune system function; and alleviate health issues associated with micronutrient deficiencies such as anemia, rickets, childhood blindness, and stunting (Bennett, Carpenter, and Caraco 2001; Hicks et al. 2019). Undernutrition contributes to the death of roughly three million children per year (Black et al. 2013), and 29 percent of the global population faced micronutrient deficiencies in 2010 (Webb et al. 2018) and an estimated 12 percent of the global population was at risk of protein deficiency in 2017 (Medek, Schwartz, and Myers 2017).

Climate change will alter temperature, precipitation, and carbon dioxide concentrations, which may have a significant impact on crop yields, although net effects on yields are still unclear (Grassini, Eskridge, and Cassman 2013; Lin and Huybers 2012; Ray et al. 2012; Ziska and Bunce 2007). Climate model projections generally indicate less precipitation in currently arid and semiarid regions and greater precipitation in the polar latitudes (Collins et al. 2013) and regional changes in extreme temperatures and heavy precipitation (Intergovernmental Panel on Climate Change [IPCC] 2018). Rising temperatures are expected to have a negative impact on major crops with each degree Celsius increase in global mean temperature causing a reduction in yield of 6 percent for wheat, 3.2 percent for rice, 7.4 percent for maize, and 3.1 percent for soybeans (Zhao et al. 2017). Warming temperatures can also increase the survival of insect pests in the winter, increasing their number and expanding their range (Bale et al. 2002; Bebber, Ramotowski, and Gurr 2013), and the spread of invasive plants and animals spurred by climate change may do significant damage to crops (Ziska et al. 2011). Crop pathogens, fungi, and weeds may also increase (Flood 2010). Extreme weather events such as prolonged heat, drought, and excessive rainfall, which are increasingly frequent with climate change, have also been shown to decrease crop yields in some cases (Lesk, Rowhani, and Ramankutty 2016; Powell and Reinhard 2016; Mäkinen et al. 2017; IPCC 2018). However, in isolated regions and for certain crop types weather extremes have actually increased yields (Mäkinen et al. 2017). Increasing concentrations of carbon dioxide may improve crop performance by increasing rates of photosynthesis and water use efficiency (Long et al. 2006; Ziska and Bunce 2007). The expected net effect of these various elements of climate change on crop yields is less predictable.

Emerging evidence also suggests that the *CO_2 fertilization effect will drive reductions in crop nutrient content*. The protein content of grains and tubers, such as rice, wheat, barley, and potatoes may decline 7–15 percent, and zinc and iron concentrations in cereal grains and legumes may decrease 3–11 percent (Myers et al. 2014). Rising CO_2 concentrations put hundreds of millions at risk of zinc, iron, and/or protein deficiency (Myers et al. 2017).

Climate change is likely to alter access to fish populations as ocean temperatures shift, and reduce fishery production. Changes in temperature patterns in the ocean are already driving shifts in the location and average depth of fish stocks (Perry et al. 2005; Nye et al. 2009). Changing locations can change access for local fishing communities or price of seafood, which may reduce access to seafood protein especially for lower-income communities (Hicks et al. 2019). Though fish distributions are changing and expected to continue to change, it is still uncertain if net fish production and fishery productivity will be altered by climate change (Brander 2007; Free et al. 2019; Smale et al. 2019; Cheung et al. 2010). Coral reefs are the habitat type most threatened by climate change due to rising ocean temperatures and ocean acidification, with projections of significant loss of area and local extinctions of these habitats (Burke et al. 2011; Hoegh-Guldberg et al. 2007; Hughes et al. 2017; IPCC 2019), and in many tropical countries coral reefs account for a significant amount (10–12 percent) of fish caught; up to 25 percent in developing tropical nations (Garcia and de Leiva Moreno 2003). It is also possible that changes in climate may alter the nutritional composition of phytoplankton communities (the basis of many marine food chains), resulting in changes to nutritional content of fish; however, further study of these micronutrient changes is needed to determine their specific impacts on human health (Myers et al. 2017).

Naturally Sourced Medicines

Although not yet clear how, climate change may alter the distribution of medicinal resources found in nature, and their chemical compounds. Tree, plant, algal, and terrestrial and marine animal extracts contain a variety of bioactive compounds such as polyphenols (including flavonoids, phenolic acids, tannins), phytoestrogens (including lignans), stilbenes, carotenoids, and sterols (Marris 2006; Holmbom et al. 2007; Moutsatsou 2007), the properties of which can result in anticancer activity, antiatherogenic potential, and antioxidant potential (Kris-Etherton et al. 2002; Karjalainen, Sarjala, and Raitio 2010). Natural medicines are still the primary source of treatments in some countries, with up to 80 percent of the population using traditional forms of medicine (World Health Organization 2002). Pharmaceutical extracts of natural materials or synthetics designed to mimic them account for a large number of today's western medicines. For example, the precursor to today's aspirin was prepared from willow bark as early as 400 BCE (Mahdi et al. 2006). Today's leading malaria drug, artemisinin, was originally derived from leaves of the Asian wormwood plant, *Artemisia annua* (Miller and Su 2011). Climate change may drive variation in the concentration and effectiveness of medically active compounds in some plants (Gairola et al. 2010; Mishra 2016). There has been recent interest in marine bioprospecting, especially with regards to new anti-infective drugs derived from marine microbes (Xu et al. 2018), but marine microbes are also vulnerable to climate change (Webster and Hill 2007), meaning important medicinal microbes may never be discovered. It is uncertain how climate change will alter the distribution of medicinal plants and the concentration of their active compounds, but it is clear that the habitats where they grow are under stress and will be changing (Gairola et al. 2010; Khanum, Mumtaz, and Kumar 2013; Maikhuri et al. 2018; Zhao et al. 2018).

Regulating Services

Pollination

Pollination by native insects is an important regulating input to many crops that benefit human nutrition. Bees are generally the main providers of pollination services, but insects, birds, bats and other animals, also contribute (FAO 2019). Crops at least partially pollinated by animals account for 35 percent of global food production (Klein et al. 2007) and are particularly significant in the supply of micronutrients for human consumption, for example, accounting for more than 90 percent of available vitamin C and more than 70 percent of available vitamin A (Eilers et al. 2011).

Climate change may affect food production of flowering species by reducing the abundance of pollinating insects and shifting their regional distributions (Abrol 2012; Hegland et al. 2009; Memmott et al. 2007; Potts et al. 2016). Warming affects the timing of flowering and will generally cause plant communities to migrate poleward (Parmesan and Yohe 2003); however, it is less likely that pollinators and their life cycles will shift in tandem. Both pollinator and flowering plant species may be at risk of extinction because of the reduced overlap in timing of flowering and pollinator emergence (Myers et al. 2017). Modeling indicates that global pollinator declines will influence adult intake of foods that provide vitamin A and folate, increasing the risk of heart disease, stroke, diabetes, and certain cancers (Smith et al. 2015).

Inland Flood Reduction

Ecosystems can help reduce inland flood risk during moderate storms by capturing and slowing down floodwaters and helping floodwaters infiltrate into groundwater (Burek et al. 2012; Dixon et al. 2016; Watson et al. 2016). Using simulation modeling at a regional scale in Europe, Burek et al. (2012) found that natural ecosystems could reduce twenty-year peak floods by up to 15 percent locally and 4 percent regionally. Even slight flood reductions can make the difference between a small flood and a disaster if it means stream banks and levees hold. Climate change is already accelerating the frequency and intensity of storms, increasing flooding in many areas (Collins et al. 2013; Kundzewicz et al. 2008; Wobus et al. 2017). These increases amplify the value of nature's regulating role in reducing flooding and storm surge from moderate sized storm events. At the same time, more frequent large events exceed the capacity of natural systems to regulate water flows and reduce floods. Under increased CO_2 conditions plants close their stomata and transpire less water, leading to more water in streams (Fowler et al. 2019). Although this may be helpful in low water conditions, it could contribute to greater flood risk in some areas. Worsening flooding and reduced ability of natural systems to mitigate these events results in the direct health impacts of flooding on loss of life and injury, but also may result in increases in chronic respiratory illness that have been observed after floods (Jakucbicka et al. 2010). In addition, increased contamination from overwhelmed septic systems, water treatment facilities, and animal agriculture will affect water sources including groundwater, which supplies 31.5 percent of the global population with drinking water. This is likely to enhance outbreaks of enteric illness (Andrade et al. 2018; Murphy et al. 2017).

Coastal Protection

Coastal habitats can reduce impacts from storm surge, sea level rise, and coastal flooding. Numerous studies have found that coastal ecosystems (salt marshes, mangroves, bivalve reefs, seagrass, coral reefs, barrier islands etc.) can help attenuate storm surge, stabilize eroding coastlines, reduce the force of incoming waves, and reduce coastal storm damages and injury (Das and Vincent 2009; Gedan et al. 2011; Shepard et al. 2012; Bayas et al. 2011). Although these natural systems can attenuate impact to coastal communities, they cannot stop it completely. One study determined that salt marsh vegetation was responsible for 60 percent of the wave attenuation during storm events (Möller et al. 2014). In the Philippines mangroves currently reduce flooding that affects over half a million people, 23 percent of whom live below the poverty line (WAVES 2017; Beck et al. 2018). For a given twenty-five-year event (flooding level expected to occur every twenty-five years) coral reefs currently reduce flooding for more than 8700 km^2 of land and 1.7 million people; these benefits increase for larger events (Beck et al. 2018).

Climate change—through influences on ocean acidification, marine heat waves, sea level rise induced inundation, coastal erosion, and saltwater intrusion—threatens protective coral reefs, mangroves, and marshes (Scavia et al. 2002; Smale et al. 2019; Speers et al. 2016). For example, the IPCC (2018) reports a 70–99 percent predicted further decline in coral reefs, depending on the future climate scenario. In addition, climate change through sea level rise and increased storm intensity will likely result in higher high tides and larger and more frequent storm surges and coastal flooding, all of which are particularly problematic for heavily populated, low-lying areas (Knutson et al. 2010; Vitousek et al. 2017; Wahl et al. 2015).

Increases in coastal flooding are primarily driven by climate change induced sea level rise and increased storm intensity, but this is exacerbated by the loss of coastal habitats from human development. Coastal flooding leads to health impacts including immediate deaths and subacute morbidity and mortality, specifically, from related outbreaks such as hepatitis E, gastrointestinal diseases, and leptospirosis, which are associated with sewage runoff and displaced populations, as well as associated physiological distress (Alderman, Turner, and Tong 2012; Lane et al. 2013; Wright, D'Elia, and Nichols 2019).

Another factor to consider is the capacity of some coastal systems, like seagrass ecosystems, to sequester, kill, and inhibit waterborne pathogens, reducing the likelihood of human exposure. This is particularly important when there is increased sewage and wastewater runoff associated with coastal flooding or overflow of combined sewer-stormwater systems in urban centers following extreme rainfall events. Unfortunately, climate change-induced increased storm frequency combined with coastal human development is driving losses in the extent of these habitats (see Case Study 1).

CASE STUDY 1 CLIMATE CHANGE INFLUENCES THE CAPACITY FOR SEAGRASS ECOSYSTEMS TO SEQUESTER WATERBORNE PATHOGENS

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Disease outbreaks in marine environments are expected to increase in the coming years because of expanding human populations on the coast and associated heightened contaminant and pollutant runoff (Grant et al. 2012). Natural ecosystems like seagrasses may represent a mitigation mechanism. Seagrasses and their microbiome have shown chemical and biological regulation of pathogens in vivo (Kumar et al. 2008; Mani, Bharathi, and Patterson 2012). A recent study revealed that the presence of intact seagrass beds resulted in 50 percent reductions in the relative abundance of potential bacterial pathogens capable of causing disease in marine organisms and people (Lamb et al. 2017). Pathogens affected included eleven of twelve of the most critically important groups of antibiotic-resistant pathogens reported this year by the World Health Organization (WHO).

The pathogen-reducing services of seagrasses may extend to other aspects of human health through indirect pathways. Coastal communities can rely heavily on coral-reef associated fish for protein and micronutrients, with fishery productivity dropping three-fold in some cases of reef loss (Rogers, Blanchard, and Mumby 2014). Seagrasses adjacent to reefs can protect this contribution to nutritional health by keeping corals free from disease (Burke et al. 2011). Nutritional health could also be improved through aquaculture practices supported by seagrasses (Troell et al. 2014).

Climate change may have profound implications for the ability of seagrass ecosystems to mitigate waterborne pathogens by further altering their distribution, productivity, and community structure. Seagrass is found on every continental shelf except for Antarctica but has declined globally with the rate of loss on the rise since 1990 (Waycott et al. 2009). It has been suggested that seagrass may actually benefit from rising levels of carbon dioxide through increased photosynthesis and carbon acquisition that support increased growth rates or densities (Borum et al. 2016). However, predicted increases in sea level and tidal range could reduce seagrass extent. Hurricanes, cyclones, and other storms cause disturbance that has resulted in seagrass decline in many parts of the world (Orth et al. 2006), and climate change is expected to increase the intensity of extreme weather events and reduce periods between them (Hoyos et al. 2006). Finally, acidification could negatively influence microbial functional diversity, reducing some pathogen control mechanisms.

Water Quality Regulation

Natural ecosystems, such as seagrasses, forests, and riverbanks, purify water through the filtration of contaminants (heavy metals, pathogenic microorganisms, etc.) and through the sequestration of nutrients that can become pollutants in high concentrations (nitrogen and phosphorous) (Burge et al. 2016; Mitsch et al. 2001; Pizzuto 2012; Tufenkji, Ryan, and Elimelech 2002).

In many places climate change is expected to increase the quantity and intensity of rainfall, which may reduce the ability of natural habitats to capture and filter pollutants because of high-volume water flows and increased upstream erosion exacerbating pollutant and nutrient runoff (Delpla et al. 2009; Kistemann et al. 2002; Kundzewicz et al. 2008; Melillo 2014).

As a result, previously sequestered contaminants, such as mercury or arsenic, can get released into waterways and food chains, which can affect human health. For example, exposure to mercury has been associated with neurocognitive deficits, multiorgan impairment (e.g., kidney, heart, liver), and reduced immune function (Bellanger et al. 2013). High levels of nitrogen in drinking water can cause methemoglobinemia (World Health Organization 2011), reproductive problems (Kramer et al. 1994), and cancer (non-Hodgkin's lymphoma, bladder and ovarian cancer) (Weyer et al. 2001).

Nutrient pollution also commonly drives eutrophication (overfertilization of waterways), which may cascade into harmful algal blooms. Human contact of high toxin by-products from algal blooms can occur through swimming, respiration (aerosols that contain toxins), or consumption of contaminated drinking water, fish, or shellfish (Cooke and Kennedy 2009; Smith 2003; Van Dolah 2000). Around 10 percent of foodborne disease outbreaks in the United States and over 60,000 global intoxication incidents per year are from algal toxins. In coastal marine habitats, these harmful algal blooms can also lead to fishery closures that limit access to seafood for seafood dependent communities. The frequency, growth rate, and longevity of these harmful algal blooms is likely exacerbated by climate change through increased water temperatures (Gobler et al. 2017; Hallegraeff 2010) and the loss of natural filtration habitats (e.g., sea grasses and forests bordering streams).

Air Quality Regulation

Ecosystems also provide a *regulating service by helping to clean our air and reducing exposure to air pollutants that cause respiratory diseases* (including asthma), cardiovascular diseases, adverse pregnancy outcomes (such as preterm birth), and even death (Haines and Patz 2004). Certain tree species improve air quality by filtering out gases and airborne particulates such as ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter smaller than 10µm (particulate matter [PM]10) (Bowler et al. 2010; Lindgren and

Elmqvist 2017). For example, trees in the contiguous United States removed 17.4 million metric tons of air pollution in 2010 (range: 9.0–23.2 million metric tons), which was calculated to avoid more than 850 incidences of human mortality and 670,000 incidences of acute respiratory symptoms (Nowak et al. 2014). Globally, street trees in urban areas are providing reductions in particulate air pollution for millions of people (McDonald et al. 2016). These benefits are concentrated in urban areas where both sources of air pollution and human populations are greatest.

Climate change is likely to inflict particular stress on urban and suburban trees through increases in pests and pathogens (Meineke et al. 2013; Tubby and Webber 2010) making it more difficult to sustain healthy urban tree cover that filters air pollution. *Climate change will also increase air pollution levels* through increases in ozone (Beggs 2004; Bloomer et al. 2009; Fiore, Naik, and Leibensperger 2015; Jacob and Winner 2009), making this air-filtration ecosystem service ever more important. Air pollution concentrations have worsened in almost 70 percent of cities around the globe between 2010 and 2016 (Watts et al. 2018).

Heat Regulation

Vegetation, especially trees, significantly help reduce local air temperatures. Loss of forests between 2000 and 2010 resulted in warming of 0.38 ± 0.02 (mean ± SE) and 0.16 ± 0.01°C in tropical and temperate regions respectively. In tropical regions, where average temperatures are already near human physiological thresholds, a 50 percent reduction in forest was associated with an increased local surface temperature of 1.08 ± 0.25°C (~2°F) (Prevedello et al. 2019) (See Case Study 2). In urban areas around the world, street trees are already providing over sixty-five million people with a 0.5 to 2.0°C (0.9 to 3.6°F) reduction in maximum air temperatures (McDonald et al. 2016).

CASE STUDY 2 CLIMATE CHANGE AND DEFORESTATION INFLUENCE THE CAPACITY OF TROPICAL FORESTS TO COOL COMMUNITIES AND BENEFIT HEALTH

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Tropical forests can provide cooling services that benefit the health of local communities. Shade from trees reduces ground level solar radiation and individual tropical trees transpire hundreds of liters of water a day for a cooling power equivalent to two household air conditioning units (Ellison et al. 2017). In rural villages in East Kalimantan, Indonesia, one study (Masuda et al. 2019) found temperatures between 2.6 and 8.3°C higher in open fields compared to nearby forests—a temperature differential so large it is equivalent to nearly a century of projected warming under high greenhouse gas emissions scenarios (Rogelj, Meinshausen, and Knutti 2012). In this same Indonesian region, a randomized control trial found significant effects of forest temperature regulation on heat stress and cognitive function (Masuda et al. 2019; Suter et al. 2019).

The cooling services provided by forests will likely become more important under climate change, especially in the tropics. Communities in low-latitude tropical countries are already exposed to thermal thresholds reaching unsafe levels (Mora et al. 2017). These communities are especially at risk of heat-related illness because many are engaged in subsistence agriculture or other manual labor, occupations that are particularly vulnerable to increases in heat exposure (United Nations Environmental Programme 2016). They also often lack access to infrastructure and alternative livelihood options. As a result, expected additional heat exposure driven by climate change could further erode their already low resilience to environmental, economic, and other shocks (Coffel, Horton, and de Sherbinin 2017), which in turn increases risks of creating and perpetuating poverty traps (Barrett, Garg, and McBride 2016). Simultaneous deforestation is likely to further heighten the loss of cooling services from forests. Additional impacts from excessive heat exposure include increased risk of injuries or accidents (Spector et al. 2016; Crowe et al. 2015), adverse mental health impacts (Berry, Bowen, and Kjellstrom 2010), kidney disease (Wesseling et al. 2013; Crowe et al. 2013), and even death (Barreca et al. 2013). In the long-term, deforestation events increase CO_2 in the atmosphere and lead to increasing incidence of extreme heat events, chronic temperature increases, and unpredictable weather patterns (Bonan 2008; Lawrence and Vandecar 2015; Lawton et al. 2001).

This can be an important factor during extreme heat events, which are becoming more frequent globally under climate change. One quarter of global landmass has experienced an intensification of heat extremes (maximum temperature in the hottest day of the year) by more than 1°C (1.8°F) over just a few decades (Schleussner, Pfleiderer, and Fischer 2017). Climate-induced changes in temperature combined with exposure show that vulnerability to extremes of heat has risen since 1990, with 157 million more people exposed to heatwave events in 2017, compared with 2000 (Watts et al. 2018). High temperatures over 39°C (102°F) have been linked to heatstroke and cardiovascular and renal disease (Watts et al. 2018; Kovats and Hajat 2008).

Fire Regulation

Natural fires produce a regulating service that reduces the risk of catastrophic wildfire. Natural small and frequent surface fire burns in grasslands and fire-associated forests maintain the habitats and associated species and reduce the fuel load, limiting the frequency of catastrophic wildfire (fires that kill a majority of trees in the canopy and can cause significant economic and ecological damage) (Pausas and Keeley 2019). Frequent fires reduce fuel load and establish a pattern of smaller, more frequent fires, which produce overall less smoke over time than catastrophic wildfires. Severe wildfires have the potential to be devastating to human communities through direct loss of life and property but also indirectly through impacts to water and air quality. Wildfires may release significant amounts of sediment (Silins et al. 2009), nutrients (Smith 2003), heavy metals (Kelly et al. 2006), and other contaminants (Crouch et al. 2006) with implications for the supply of safe drinking water (Bladon et al. 2014; Emelko et al. 2011).

Wildfires can also produce massive plumes of smoke over wide areas. Average global mortality from landscape fire smoke exposure between 1997 and 2006 was 339,000 deaths annually with the highest rates in sub-Saharan Africa and Southeast Asia (Johnston et al. 2012). Following large 1997 fires in Indonesia, an estimated twenty million people in that country suffered from respiratory problems, with 19,800–48,100 premature mortalities (Heil, Langmann, and Aldrian 2007). Peatland forest fires with dangerous levels of airborne particulate matter now occur almost every year in Indonesia (Harrison, Page, and Limin 2009). In the western United States, about forty-six million people of all ages were exposed to at least one smoke wave (two consecutive days of wildfire-related $PM_{2.5} > 20\ \mu g/m^3$) during 2004 to 2009 and experienced a 7.2 percent increase in risk of respiratory-related hospital admissions during smoke wave days (Liu et al. 2017). Levels of PM10, the most frequently studied pollutant, were 1.2 to 10 times higher due to wildfire smoke compared to nonfire periods and/or locations (Liu et al. 2015). Respiratory disease was the most frequently studied health condition and had the most consistent results, with exacerbations of asthma, chronic obstructive pulmonary disease, bronchitis, and pneumonia. Recent studies now also report an increased risk of respiratory infections and associated mortality (Reid et al. 2016) and reduced height in adulthood (Tan-Soo and Pattanayak 2019). Although the loss of natural fire regimes (fire regulation service) is a driver for increased large-scale wildfires and associated smoke events, it is not the only one.

Climate change is increasing these risks because it is leading to earlier and longer fire seasons (Intergovernmental Panel on Climate Change 2013; Pechony and Shindell 2010; Westerling et al. 2006). Future wildfire potential increases significantly with climate change in the United States, South America, central Asia, southern Europe, southern Africa, and Australia (Liu, Stanturf, and Goodrick 2010). Climate change has already increased wildfire activity across forests in the western United States, lengthened the fire season, and doubled the cumulative area that would have burned in this same region between 1984 and 2016 (Abatzoglou and Williams 2016; Harvey 2016). Much of the western United States and areas around the Great Lakes and southeastern coast are predicted to have three to six times more weeks with “very high risk” of fire by midcentury (Barbero et al. 2015).

Climate Regulation

Natural ecosystems can directly regulate the climate by drawing down greenhouse gases from the atmosphere. As plants use carbon dioxide in photosynthesis, terrestrial ecosystems absorb around three billion tons of atmospheric carbon per year through net growth, which accounts for 30 percent of anthropogenic CO_2 emissions (Canadell and Raupach 2008). Tropical forests that hold around 250 Gt of carbon have become a net source of carbon emissions due to deforestation and degradation, releasing over 400 Tg (10^{12} g) C each year (Baccini et al. 2017; Saatchi et al. 2011). The other natural system with high carbon storage is the northern permafrost. Around 1,500 billion tons of organic carbon are stored in terrestrial soils in the northern permafrost zone but *increasing temperatures from climate change are starting to thaw it, releasing methane* (a more powerful—five to twenty times, but shorter-lived greenhouse gas than carbon dioxide). Models estimate around ninety billion tons of this carbon will be released by 2100 with more than half being lost after that (Schuur et al. 2015). Oceans and the phytoplankton within them are also a significant reservoir of carbon, taking up around 1.4 Pg C per year (Landschützer et al. 2014); the ocean has absorbed between 20 and 30 percent of anthropogenic carbon dioxide emissions since the 1980s (IPCC 2018, 2019). Griscom et al. (2017) postulate that if all terrestrial and coastal habitats were managed to maximize carbon sequestration (e.g., reforestation, agricultural management) with reasonable safeguards to maintain sufficient food production and **biodiversity** support, an additional 2.3 Pg (10^{15} g) CO_2 equivalents could be captured. This could provide one third of the mitigation needed to give us a two-thirds chance of staying below a 2°C climate threshold.

As climate change alters plant distribution patterns and growth rates, it is likely to affect climate regulation. As noted previously, the climate-driven melting of permafrost will release large amounts of potent greenhouse gases, creating a reinforcing feedback loop that will accelerate climate change (Schuur et al. 2015). In terrestrial ecosystems increased carbon dioxide has a “fertilization effect” on vegetation by increasing the efficiency of photosynthesis as long as there is enough nitrogen (the most commonly limiting element) for the plants. This is likely to increase the carbon stored in terrestrial vegetation; however, rates of decomposition and carbon loss from soils is likely to increase and the net effect in non-permafrost regions is not certain (Bonan 2008). Loss of natural ecosystems’ abilities to regulate the global climate connects back to human health through the myriad linkages highlighted in this book.

Infectious Disease Regulation and Biodiversity

Climate change can influence the severity, timing, and location of infectious disease outbreaks by altering host susceptibility, infectious agents, and environmental conditions including temperature, humidity, and preferred habitat for vectors. Climate change is also shifting the spatial distribution of vector-borne and zoonotic diseases like Lyme disease, malaria, dengue, Zika, and viral encephalitis into historically cooler climates that are now warming (Gage et al. 2008; Githeko et al. 2000; Patz 2018; Patz and Reisen 2001). For mosquito-borne diseases, warmer temperatures can also exacerbate risk by increasing egg production, biting rates, and shortening the disease incubation time (Patz et al. 1996). At the same time, human migrations and travel of disease naïve populations into areas newly in range for these vector-borne diseases may mean less immunity in these communities and greater disease risk (Patz and Reisen).

Another way in which climate change may affect human disease is through losses in biodiversity resulting from altered temperature, precipitation, and hydrologic systems. The so-called "**dilution effect**" posits that changes in biodiversity in some ecosystems will impact the transmission cycle of certain pathogens. Where biodiversity is higher, the presence of hosts with a low capacity to transmit disease from host to vector can dilute the effect of highly competent hosts (Ostfeld and Keesing 2012). Conversely, reductions in diversity from climate change may increase infection risk and disease prevalence in hosts. Although there is mixed evidence about the importance of the dilution effect, empirical studies often find that decreased diversity is correlated with increased disease risk (Young et al. 2017). Appropriate policy response to these risks remains unclear, in part because climate change and other forms of disturbance affect disease through additional pathways (Young et al. 2017).

Cultural Services

Nature provides aesthetic and psychological benefits that enrich human life with meaning and emotion, and have direct connections to mental health (Chiesura 2004; Yeager et al. 2018). Aesthetic benefits from green spaces have been associated with reduced stress and with increased mental health (Berg et al. 2010; Stigsdotter et al. 2010). The use of urban green space, such as urban community gardens and other activities that enhance a sense of place, social interactions, and the strengthening of neighborhood participation, has been shown to have beneficial mental health effects (Elmqvist et al. 2013; Lindgren and Elmqvist 2017). As noted previously, climate change is likely to inflict particular stress on urban and suburban trees (Tubby and Webber 2010; Meineke et al. 2013), where green spaces are likely to be most limited and most needed.

Many communities, including Indigenous and rural, have strong cultural associations with natural ecosystems; for example, plants and animals that represent deities, access to burial grounds or family places, sufficient subsistence resources like fish or clean water, and engaging in cultural fishing or harvest practices (Pascua et al. 2017). Climate change is having disproportionate effects on some such cultural services. For example, in the Arctic, weaker sea ice and reduced longevity of ice reduces travel options and speed, and sea ice-based hunting. In addition, thawing permafrost can damage roads and infrastructure reducing access to important sites for Indigenous people (Hovelsrud et al. 2011). Low-lying small island nations are at great risk from sea level rise with entire cultural heritages at risk (Barnett and Adger 2003). These changes in the provision of cultural services driven by climate change dramatically affect cultural practices, nutrition, and mental health.

Table 29.1 summarizes the ecosystem services discussed in this section.

Table 29.1 Summary of Ecosystem Services Discussed, How Climate Affects the Ecosystems Those Services Depend on, and the Human Health Impacts Related to Those Altered Services

	Ecosystem Services	Climate Change Impacts	Ecosystem Effects	Health Impacts
Provisioning	**Crops**	Changing precipitation and weather patterns (storms, droughts etc.); increased CO$_2$ levels; desertification	Altered crop yield, reduced crop nutritional content, decreased soil health, increased crop pests	Food and nutrition security
	Freshwater fish	Rising water temperatures; changing precipitation patterns	Fish deaths, expansion of invasive species, increased frequency of algal blooms (causing fish death or inability to harvest fish)	Food and nutrition security
	Marine fish	Ocean acidification; rising water temperatures and changing ocean currents	Exacerbates algal blooms and dead zones, fish deaths, loss of fish nursery habitat, changing fish locations	Food and nutrition security
	Natural medicines	Climate-induced stress on habitats where medicinal organisms grow/live	Habitat loss, habitat health, ecological community shifts; range distribution shifts of medicinal organisms	Availability of and access to medicinal organisms; potential to discover new medicinal substances

	Ecosystem Services	Climate Change Impacts	Ecosystem Effects	Health Impacts
Regulating	**Pollination**	Warming temperatures; changing precipitation patterns	Changes in flower phenology; shifting (and possible mismatch) of ranges of plant and pollinator species; reduced populations or local extinction of pollinator species, all leading to reduced crop yields	Food insecurity and malnutrition due to decreased production of animal pollinated crops
	Water storage (flood protection)	Increased frequency of high intensity rainfall events	Inability of what remains of natural systems to store increased climate-change-induced floodwaters	Morbidity and mortality from floods; spread of infectious disease after flood events; mental health impacts related to flood events
	Coastal storm protection	Frequency and intensity of storms that cause significant coastal flooding; sea level rise; increased water temperatures, ocean acidification	Overwhelming of natural systems that buffer against storm surge; loss of coral reefs that buffer storm surge	Morbidity and mortality from floods; spread of infectious disease after flood events; mental health (stress) related to flood events
	Water filtration	Increased frequency of high intensity rainfall events; loss of habitats from storms, temperature, and sea level rise.	Inability of natural systems to sufficiently filter increased runoff of contaminants into waterways	Humans drinking contaminated water (e.g., contaminated with diarrheal disease-causing bacteria, heavy metals, nutrients)
	Air filtration in urban areas	Climatic conditions suitable for urban tree pests and pathogens	Pest and pathogen proliferation leading to death or decreased health of urban trees	Exposure to air pollution
	Heat regulation	Increasing temperatures and increased frequency of heat wave events	Loss of trees increases local temperatures, and pest and pathogen proliferation lead to death or decreased health of urban trees	Incidence of heat related illness, for example, heatstroke
	Reducing wildfire risk	Decreased rainfall and increased temperatures	Increased forest fire risk; spread of insect pests and pathogens that weaken trees; habitat shifts that stress trees	Morbidity and mortality from fire; exposure to smoke; contaminated freshwater sources (caused by sedimentation from fire events) with effects on drinking water quality and freshwater fisheries
	Climate regulation	Temperature and precipitation changes	Loss or reduced health of habitats that sequester and store carbon	Increased release or decreased capture and storage of carbon resulting in increased climate change (which causes all the health issues this book discusses)
	Disease regulation	Changing temperatures and precipitation patterns	Shifting and expanding ranges for disease vector species; increased vector production rates and incubation time; biodiversity loss and associated dilution effect	Increased exposure to disease carrying vectors (e.g., for malaria, Lyme); increased infection prevalence in disease hosts
Cultural	**Psychological benefits of green space/ nature exposure**	Climatic conditions suitable for urban tree pests and pathogens	Pest and pathogen proliferation leading to death or decreased health of urban trees	Reduction in mental health benefits of urban greenspace
	Cultural significance	Changing temperature and precipitation	Shifting or loss of culturally relevant habitats and species	Malnutrition related to loss of traditional food sources; mental health effects of loss or degradation of culturally relevant habitats and species

Ecosystem Solutions that Reduce Climate Change Impacts on Human Health

A diverse array of management approaches has been developed to improve the provision of ecosystem services. Most of these management approaches are not designed to reduce climate change impacts on human health, but if implemented in the right places with the right design, many could do so. Here, we provide several examples of ecosystem service management approaches that could reduce climate change impacts on human health.

Healthy soil communities store carbon and contribute to climate stabilization. Investments are already being made in management approaches like cover crops or fertilizer management to improve soil health and increase climate benefits. These same soil health improvements may benefit people by increasing the nutritional value of crops. For example, a study in Ethiopia showed that wheat grown on soils with more organic carbon had higher levels of zinc and protein (Wood and Baudron 2018).

Another example where soil health investments could which improve human health is found in northwest India is currently dominated by a rice-wheat cropping system that relies on crop residue burning to clear fields (National Academy of Agricultural Sciences 2017). This residue burning reduces soil health, and the burning itself is a major health risk, as the air pollution caused by fires contributes one quarter of high particulate air pollution levels in the winter (Sarkar, Singh, and Chauhan 2018). These pollution levels are high enough to affect the population in major cities including Delhi, where the last two years have seen national health emergencies declared during the peak burning season. Interventions that reduce crop residue burning would benefit soil health, climate, and human health.

A wide range of approaches have been designed to restore and protect forests for their carbon storage and climate mitigation benefits (in addition to their natural value). Management approaches that improve or maintain forest cover in the tropics could benefit human health by reducing heat stress (see Case Study 2). There is some evidence that efforts to protect forests in South America and Asia (but not Africa) by reducing road construction that fragments forests can reduce malaria risk (Bauhoff and Busch 2020). Some forest management approaches have been designed to help reduce wildfire risk, which is increasing under climate change (Westerling et al. 2006; Abatzoglou and Williams 2016). As these approaches are meant to reduce fires near population centers, further investment in them could also reduce smoke exposure and associated respiratory health impacts.

Investments in coastal ecosystem services can have direct climate mitigation and adaptation benefits and could also aid health if designed to do so. Investments in highly structured coastal habitats like coral reefs and mangroves can lead to reductions in storm surge and associated coastal flooding, reducing floodwater health risks, and loss of life during moderate storms. Innovative financing tools are being developed to support this ecosystem service. For example, a new kind of risk management tool called parametric insurance was recently applied to a stretch of Mexican coastline near Cancún. The insurance policy is paid for by hotel taxes, and used to recover the reef and its protective services after damage by storms.

Although many ecosystem service management options exist, it will be critical for the cost effectiveness of any ecosystem service solutions be compared to traditional health interventions. Few studies have done such comparisons. There is a need for more research on ecosystem-mediated health outcomes, especially research that focuses on how public policy responses and human behavioral changes affect ecosystems and human health (Pattanayak, Kramer, and Vincent 2017). Given the rapidly increasing pace of climate change, and increasingly clear impacts of climate on both ecosystem services and health, this is an area that warrants immediate attention from health and environment communities alike.

Summary

Ecosystem services are the benefits that nature provides to people. Many of these benefits flowing from nature influence some aspects of human health. Climate change is altering natural ecosystems on earth through a myriad of pathways thus changing their ability to provide services to people, resulting in varied human health outcomes. We have discussed how various ecosystem services affect human health and described how climate change might disrupt or alter the delivery of those services. We conclude with examples of ecosystem management activities that present possible solutions for mitigating the health effects of climate change's disruption of ecosystem services.

DISCUSSION QUESTIONS

1. Describe how climate will affect one provisioning, one regulating, and one cultural ecosystem service.
2. How might those changes identified in question 1 affect human health?
3. How might climate change influence human nutrition? What ecosystem services mediate those effects?
4. Briefly describe one example of natural resource management that could help mediate the negative health outcomes of climate change.

KEY TERMS

Biodiversity: The term biodiversity (from "biological diversity") refers to the variety of life on Earth at all its levels, from genes to ecosystems, and can encompass the evolutionary, ecological, and cultural processes that sustain life. Biodiversity includes not only species we consider rare, threatened, or endangered but also every living thing—from humans to organisms we know little about, such as microbes, fungi, and invertebrates (American Museum of Natural History, Center for Biodiversity and Conservation n.d.).

Cultural ecosystem services: Ecosystem services that describe the nonmaterial benefits that ecosystems provide to people, such as recreation opportunity, aesthetic appreciation, spiritual connection, sense of place, or appreciation for the existence of a particular habitat or species.

Dilution effect: The so-called "dilution effect" posits that changes in biodiversity in some ecosystems will impact the transmission cycle of certain pathogens. Where biodiversity is higher, the presence of hosts with a low capacity to transmit disease from host to vector can dilute the effect of highly competent hosts. Conversely, reductions in diversity may increase infection risk and disease prevalence in hosts.

Ecosystem services: Benefits people receive from nature.

Provisioning ecosystem services: Ecosystem services that represent material benefits of ecosystems that people use, appreciate, or sell. Many provisioning services have market value. These services include food production, water provision, and raw material creation (e.g., wood).

Regulating ecosystem services: Ecosystem services that regulate natural systems, such as an ecosystem's ability to regulate flooding, pollinate crops, or maintain soil health.

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