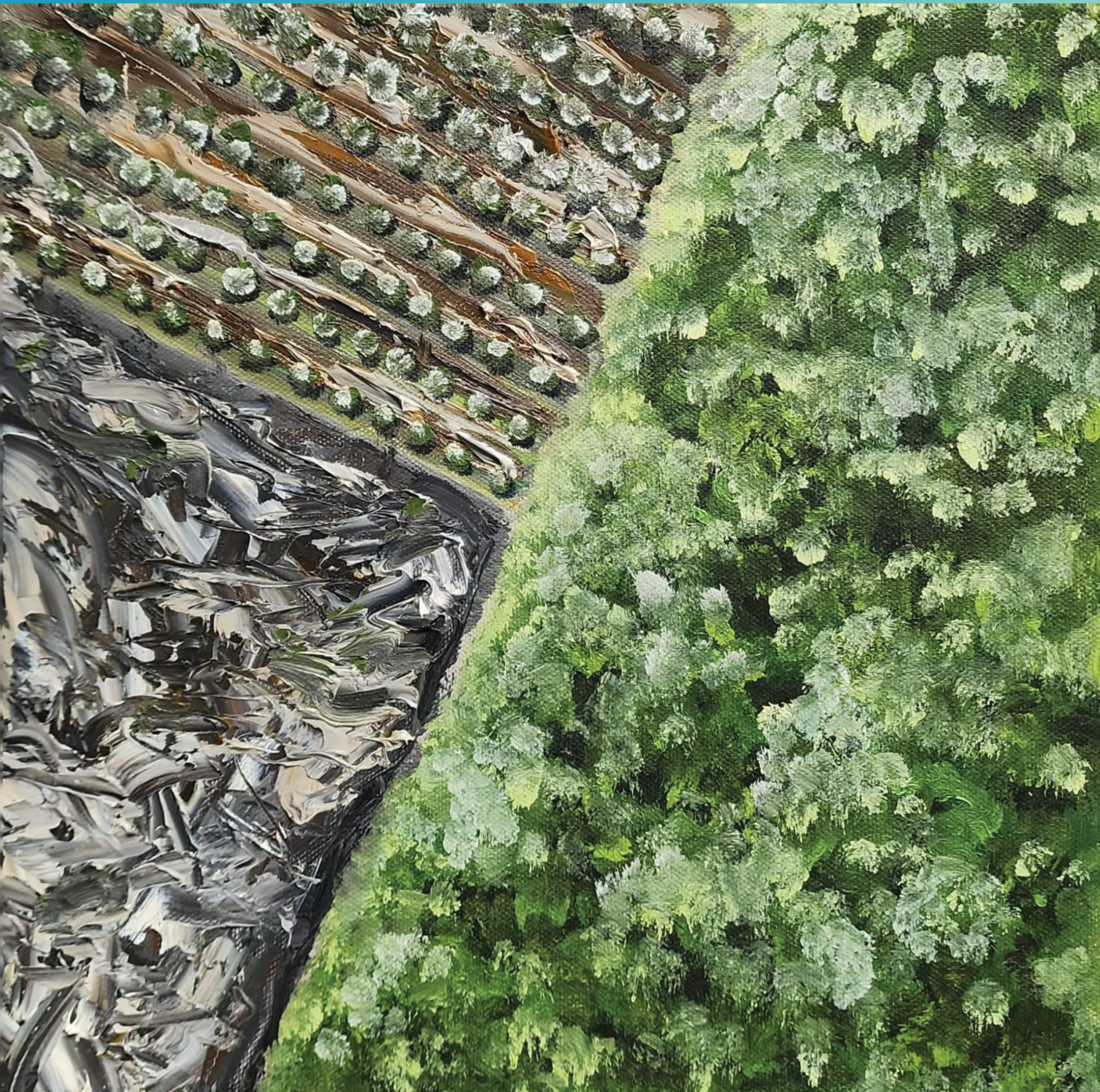
Fifth National Climate Assessment: Chapter 6

Land Cover and Land-Use Change



Dedication

We dedicate this chapter to the memory of our friend and colleague Brad Reed. Brad served as a coordinating lead author for the Land Cover and Land-Use Change chapter before he suddenly passed away. He made groundbreaking contributions to the chapter by setting up the chapter team and chapter structure. Brad was well respected throughout the USGS and the broader scientific community and was a close friend and colleague to many. He was involved in a number of research endeavors, including mapping global land cover, characterizing phenology from Earth observation data, and assessing biological carbon sequestration for the US. Brad was a pioneer in the fight against global warming and a strong advocate for the conservation of Earth's natural resources. A leader in the land-change science and Earth observation communities, Brad made great efforts to tackle society's most urgent issues.

Chapter 6. Land Cover and Land-Use

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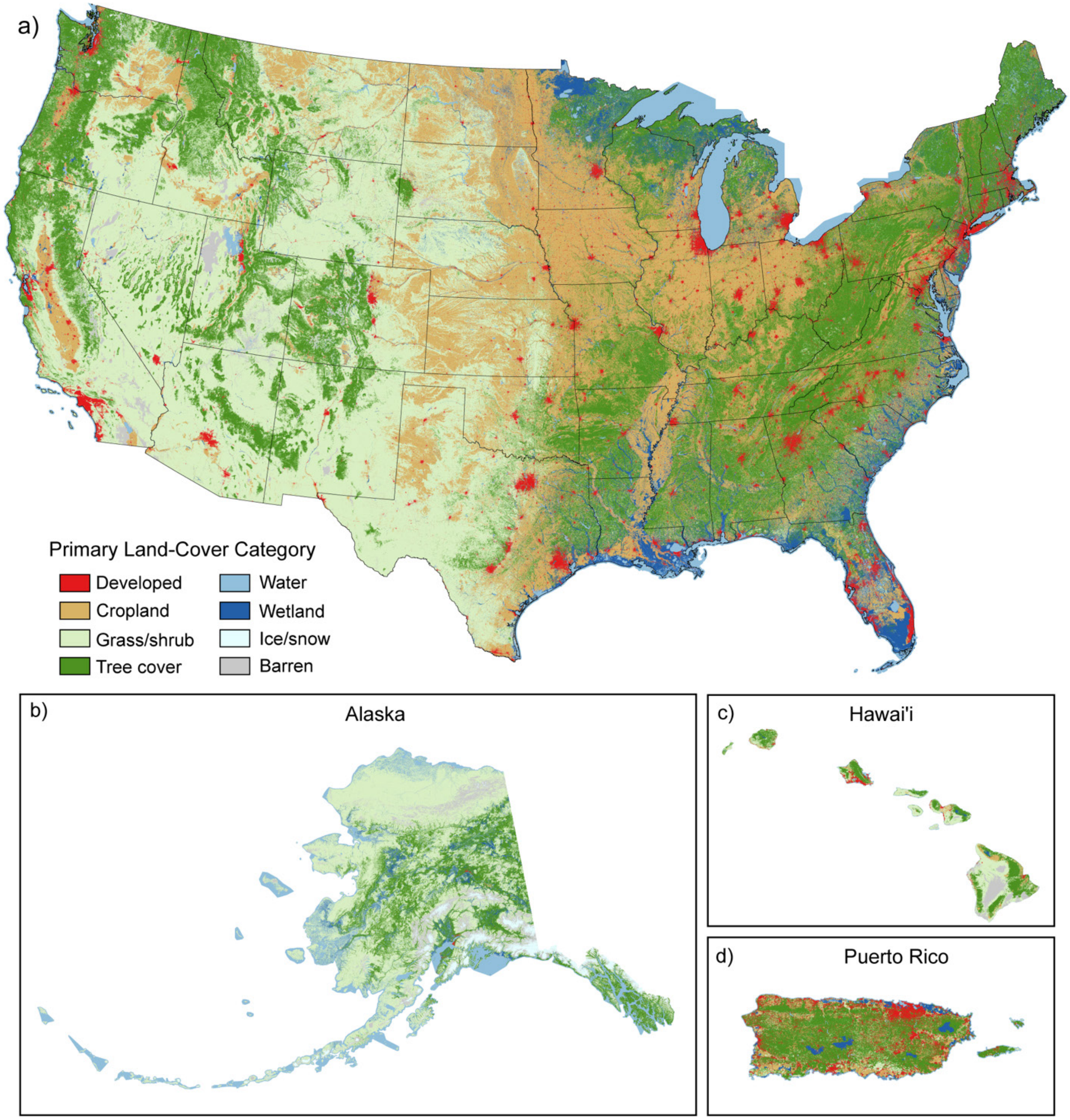
Introduction

As Earth's climate changes, many critical aspects of the land system are at risk. "Land system" refers to both land cover (the physical organization of the land surface) and land use (the intentional ways humans interact with the land). Land system here also refers to the physical and ecological functions of land and changes in organization and function over time. Escalating concerns about how climate and global environmental change impact land systems and ecosystem sustainability have driven extensive research efforts to understand these complex interactions.[1,2,3,4,5] This chapter considers three broad categories describing the value of land systems to society and risks associated with climate change: 1) goods and services provided directly by land systems, 2) resilience of land systems in the face of disturbance, and 3) availability of options for future land use.

Analysis of these topics depends in part on reliable descriptions of historical and current land cover and land use. Satellite remote-sensing platforms and ground-based training data provide records of past and current land cover over the United States on a yearly basis (Figure 6.1).[6,7,8] Land-cover changes are caused by humans and ecosystem processes, with compounding effects from climate change, and are unevenly distributed in space and time. Some areas experience frequent land-cover changes from natural or human-caused disturbance (Figure 6.2), while other areas show progressive shifts in land cover, for example with the expansion of developed areas (Figure 6.3). While broad land-cover categories are relatively stable through time when aggregated to the national scale, varying by less than 10% from their 1985 values over the period 1985–2020, modest multidecadal changes within land-cover categories are still evident (Figure 6.4).

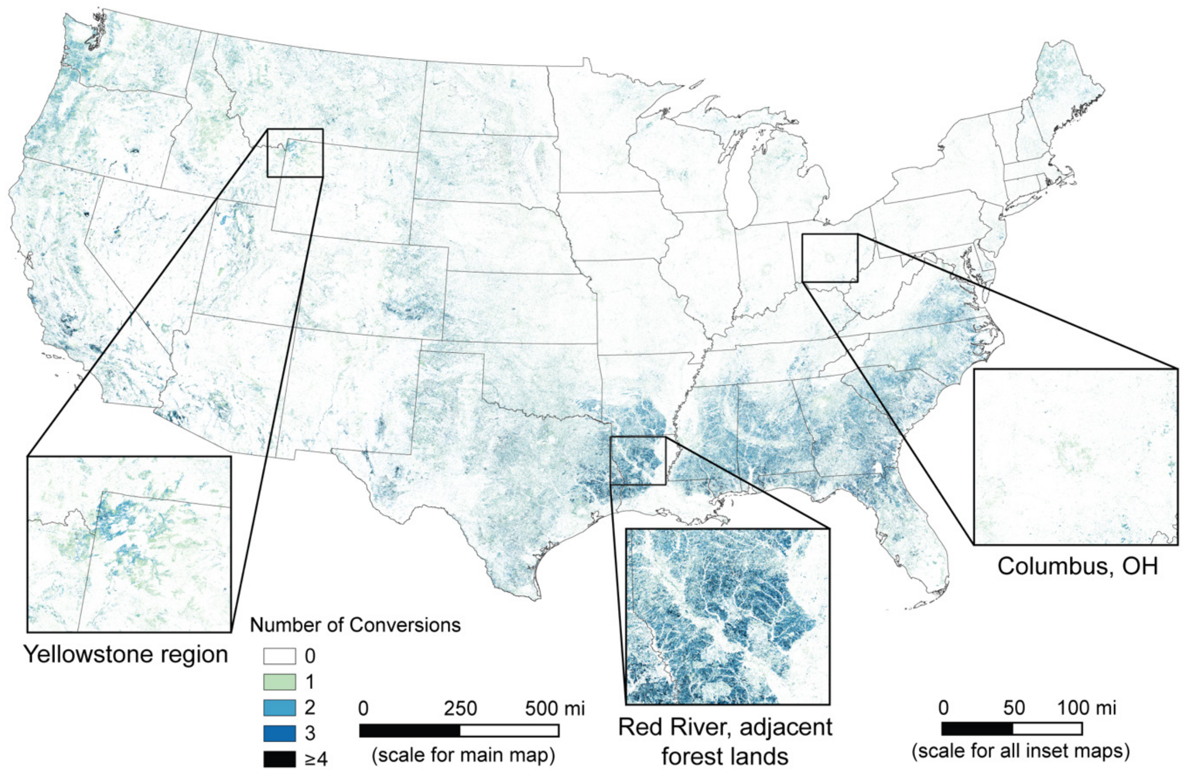
Present-Day Land Cover



The United States is characterized by complex spatial distributions of developed, managed, and natural land-cover types.

Figure 6.1. Data shown here are from different sources and for slightly differing time periods: (**a**) contiguous US from Land Change Monitoring, Assessment, and Projection [LCMAP] data for 2020; (**b**) Alaska from the National Land Cover Database for 2016; (**c**) Hawai‘i from LCMAP for 2019; and (**d**) Puerto Rico from Coastal Change Analysis Program data for 2010. Developed land cover is clustered around urban centers, croplands dominate the central contiguous US, and managed and natural forests, grasslands, and shrublands are widely distributed. Figure credit: Oak Ridge National Laboratory and USGS.

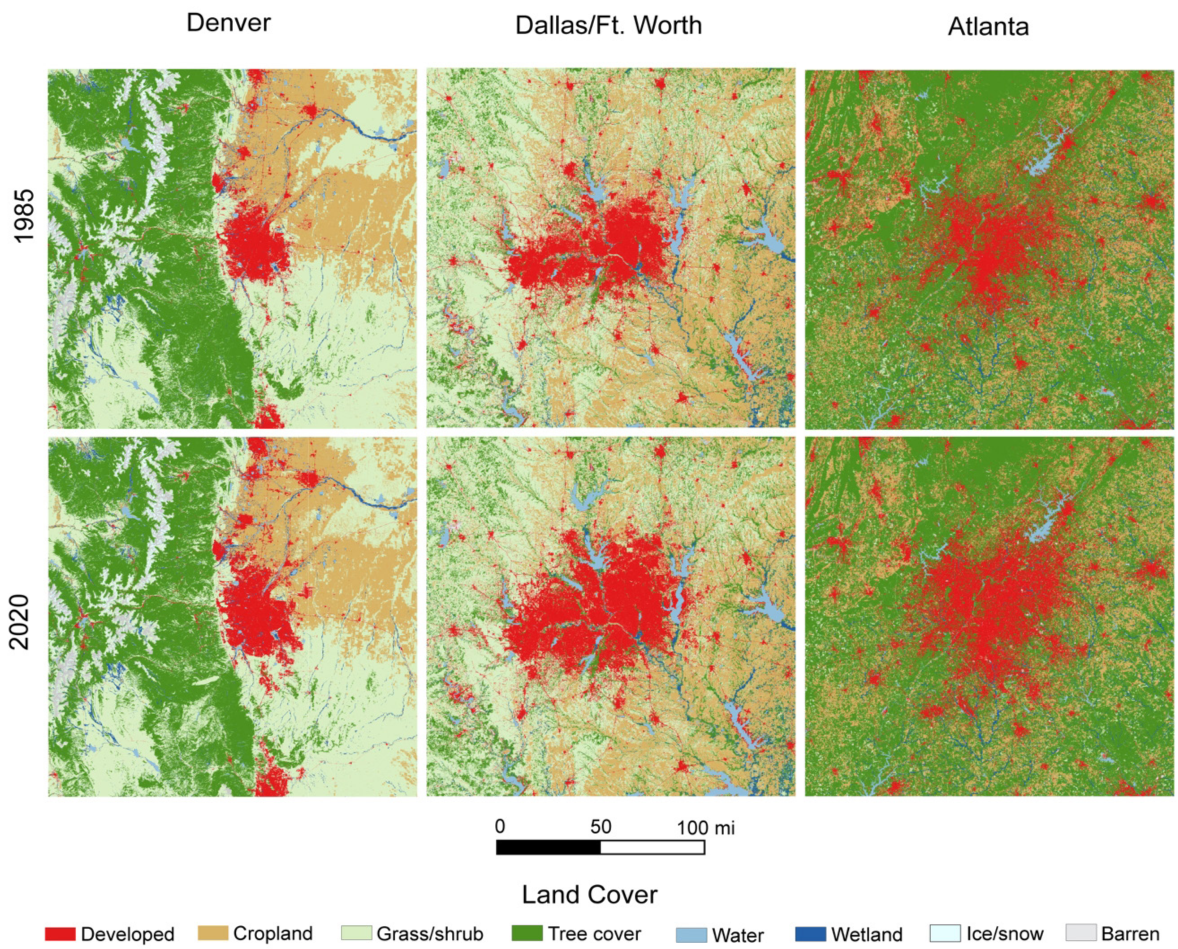
US Land-Cover Conversions, 1985–2020



Land-cover change can result from development, forest management, wildfire, and other causes.

Figure 6.2. Superimposed on the complex mosaic of land-cover types are patterns of land-cover change that vary among regions. The number of land-cover conversions is shown over the period 1985–2020. A conversion is defined for each LCMAP (Land Change Monitoring, Assessment, and Projection) 30 m x 30 m grid cell as a change between years from one primary land-cover category to another. The primary land-cover categories are as follows: developed, cropland, grass/shrub, tree cover, water, wetland, ice/snow, and barren. The frequency of conversion depends on multiple interacting factors. Development drives expansion of urban centers (e.g., around Columbus, Ohio). Forest management causes multiple land-cover conversions between forest and non-forest categories over decadal timescales while maintaining a consistent land use (e.g., around the Red River). Wildfire can cause large and long-lasting changes in land cover (e.g., in the Yellowstone region). The warming climate influences land-cover change by impacting development patterns, harvest recovery dynamics, and wildfire frequency and intensity. Figure credit: Oak Ridge National Laboratory and USGS.

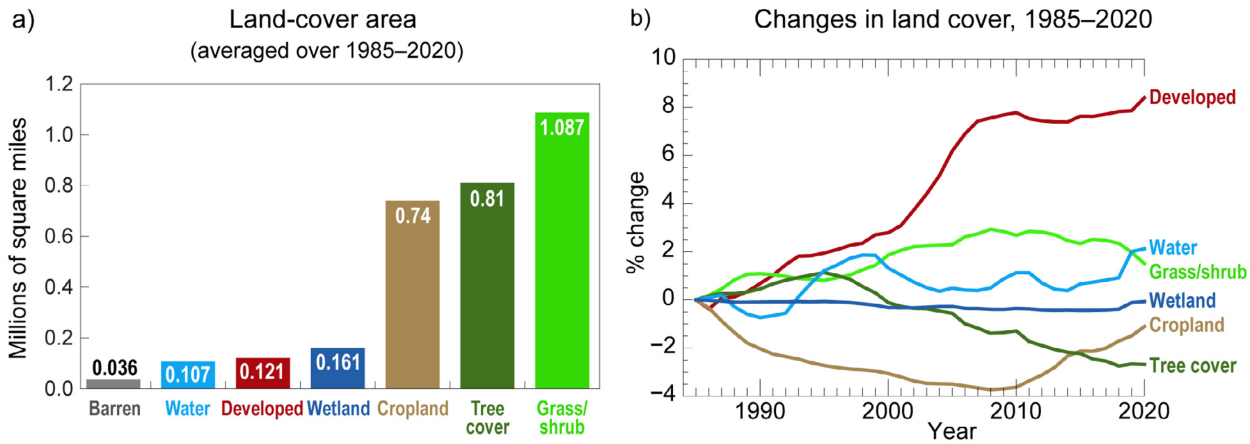
Expansion of Developed Land Cover



Increased development decreases natural and managed land cover.

Figure 6.3. Continuing expansion of development into vegetated land changes the array of climate-related risks to land system goods and services (KM 6.1), land system resilience (KM 6.2), and future land-use options (KM 6.3). Land-cover changes from 1985 to 2020 are shown for three urban areas: Denver, Dallas/Fort Worth, and Atlanta. Figure credit: Oak Ridge National Laboratory and USGS.

US Average Land Cover and Land-Cover Change



Developed land is increasing, while land with tree cover is on the decline.

Figure 6.4. Grassland, shrubland, cropland, and tree cover make up a large majority of the US land cover (**a**), and the area of these broad land-cover types changes relatively slowly over time when aggregated over the contiguous US. When expressed as a percentage change from the total land area for each cover type relative to values in 1985 (**b**), developed land has the largest increase through 2020. The area with tree cover has been declining since the mid-1990s, while the area of cropland declined through about 2010 and increased again through 2020. Figure credit: Oak Ridge National Laboratory and USGS.

Key Message 6.1

The Goods and Services Provided by Land Systems Are Threatened by Climate Change

Climate change has increased regional intensity and frequency of extreme rain, droughts, temperature highs, fires, and urban floods (*high confidence*), posing increased risks for roads and other infrastructure, agricultural production, forests, biodiversity, carbon sinks, and human health (*high confidence*). Climate-driven increases in wildfire extent and intensity are threatening the ability of some western forests to provide valued goods and services (*high confidence*). Climate change has disrupted the ways that people interact with the landscape for spiritual practices, recreation, and subsistence (*high confidence*).

Infrastructure, Public Safety, and the Built Environment

People expect land to provide a solid and permanent footing for infrastructure, public safety, and the built environment. Climate change threatens this in numerous ways, including increases in erosion, permafrost thaw, slope failure, fire, flooding, and shoreline retreat. Land-use changes themselves can interact with these climate impacts in complex ways (KM 6.2).

As sea levels rise, coastal infrastructure is increasingly exposed to risks of flooding and wave action from storm surges and nuisance flooding during high tides, with low-income coastal communities facing greater risks due to fewer resources for response (KMs 9.2, 23.1). The Atlantic and Gulf Coasts are particularly vulnerable to high tide flooding.[9] Decadal-scale variability in Great Lakes water levels drives shoreline erosion (KM 24.5). Increases in the magnitude and frequency of heavy rain in a warmer climate heighten the risk of damage from river flooding, especially where infrastructure for water storage, treatment, and transfer becomes overwhelmed. Increased storm rainfall puts roads and buildings at greater risk of damage by landslides.[10] For example, Hurricane Maria, a Category 4 storm in 2017, caused substantial damage and fatalities in Puerto Rico, as well as more than 70,000 landslides.[11]

Warming of colder regions such as Alaska presents significant risks. Damage to roads and the Trans-Alaska Pipeline System is occurring due to ground destabilization as permafrost thaws.[12,13] As steep, rocky terrain warms and thaws, rockfalls can increase,[14] and as tidewater glaciers retreat, newly destabilized slopes in front of glaciers can collapse into water, causing potentially hazardous tsunamis.[15,16]

The USGS[17] provides emergency assessment of postfire debris-flow hazards (Focus on Western Wildfires). Fire and postfire debris flows increasingly threaten infrastructure and public safety as a warming climate and increased drought raise the risk of large, intense fires.[18,19,20,21] Notable among recent examples was the debris flow following the Thomas Fire in Southern California, which killed 23 people, damaged 558 structures, closed a major highway for 13 days, and caused more than $1.15 billion in damages (in 2022 dollars; Figure 6.5).[22,23] Risks to water supply and quality continue for years after a fire, as erosion washes excess sediment and pollutants downstream,[24] shortening the lifespan of water-storage reservoirs.[24,25,26] Sediment production is projected to double in one-third of western US watersheds by 2050 due to increased fire and extreme rain.[26]

Damage from Postfire Debris Flows

Postfire debris flows threaten public safety.

Figure 6.5. Photos show property destroyed by postfire debris flows in Montecito, California, caused by intense rain on January 9, 2018, falling on areas burned by the Thomas Fire in the previous month. Both contributing events—a large wildfire and extreme rain—are projected to become more frequent with climate change. Photo credits: Jason W. Kean, USGS.

The Southwest faces additional challenges to infrastructure and public health and safety from increased airborne dust,[27,28,29] which can carry human disease and result in traffic accidents.[30,31] Vegetation loss during drought can cause marginally stable land to transition to actively migrating sand dunes, some of which damage buildings and roads.[32,33]

Agriculture: Crops and Rangelands

Land provides essential services by supporting the production of food for people, feed for animals, and forage for wildlife. Climate change has led to increased extremes of both temperature and precipitation, with increased risks to crop yield (KM 11.2) and associated impacts on land-cover and land-use change (LCLUC). Crop yields in the US continue to increase but are subject to large year-to-year fluctuations driven by environmental stresses[34,35] and have become increasingly sensitive to water availability over the past two decades.[36] Yield loss associated with warming has resulted primarily from drought, with heat stress playing a secondary role.[37] Flooding also causes crop damage; during 1981–2016 in the US, inundation-induced yield loss was comparable in magnitude to that caused by extreme drought.[38]

In arid and semiarid lands of the Southwest, livestock overgrazing, oil and gas extraction, and off-road vehicle use amplify the effects of warming[39] by damaging vegetation and biological soil crusts,[40] further increasing dust production. The spread of invasive plants exacerbates this transition, leaving landscapes less adaptable to warming.[41] Water extraction by humans lowers water tables, stressing plants, drying lakebeds, and increasing dust production. These factors, together with the warming-induced drought, reduce the productivity and carrying capacity of US rangelands (KM 28.3).

Forests and Biodiversity

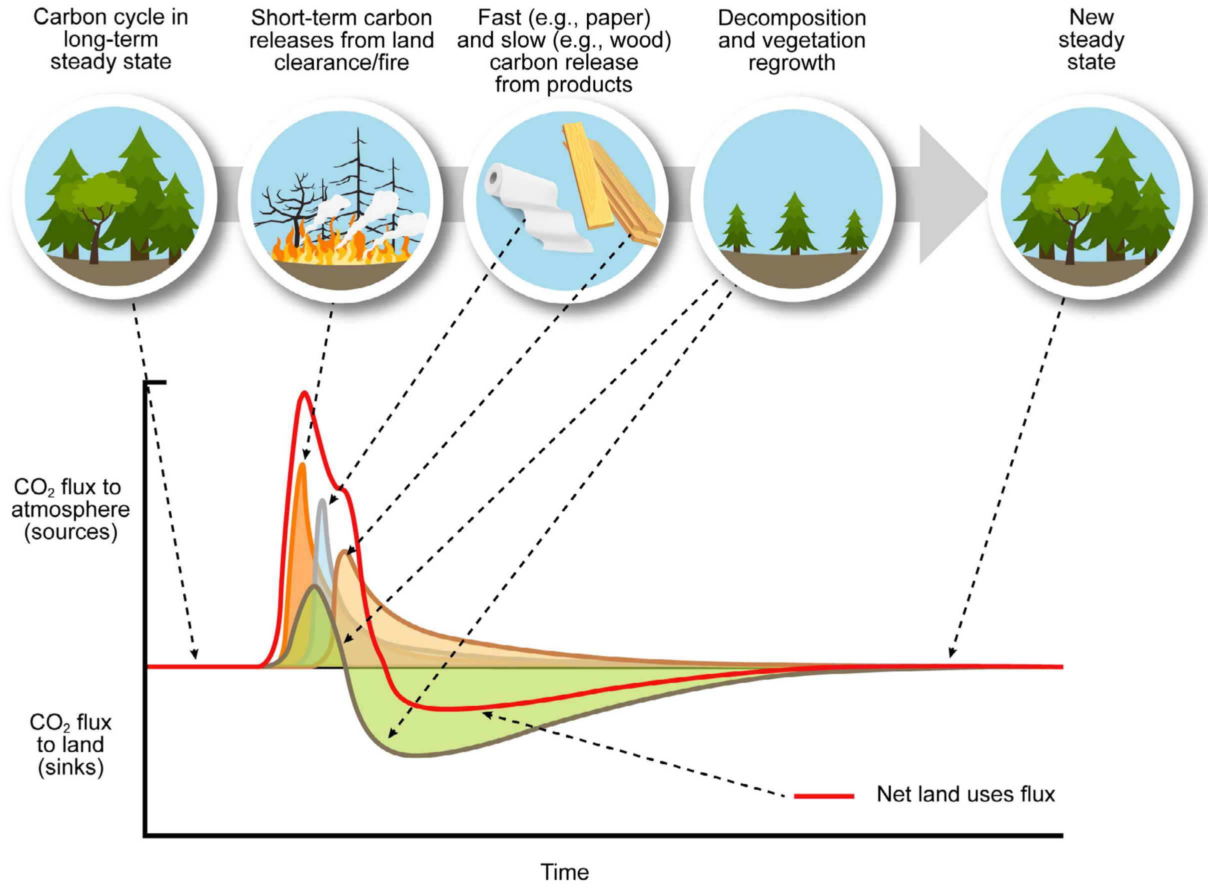
Forests provide critical value to society by supplying a wide range of wood products, protecting water quality, supporting biodiversity, and providing recreational opportunities and spiritual and cultural benefits. Forest land cover can reduce warming locally by providing increased evaporation and shade.[42] The effects of land-use change on forest goods and services, including the value of biodiversity, are still being explored.[43,44,45] In some cases, forest management can increase biodiversity and offset regional losses due to urbanization, but future losses of biodiversity due to climate change may be greater than reforestation offsets.[46]

Multiple interacting factors drive changes in goods and services from forest lands, including development, abandonment and expansion of agricultural land, and incentives for reforestation and conservation.[47] Mixed land uses such as agroforestry are expected to increase soil water infiltration compared to agriculture alone, providing protection against warming, drought, and soil erosion due to overland flow during extreme precipitation events.[48] Forest land-use transitions intended to mitigate climate change must be carefully assessed to prevent unintended consequences, such as net losses of carbon, biodiversity, habitat, soil quality, or other ecosystem services when converting mature forest to bioenergy crop cultivation (e.g., Harper et al. 2018[49]).

Natural and Managed Carbon Sinks

Land ecosystems provide an important service to society by sequestering a fraction of the carbon emitted to the atmosphere through fossil fuel combustion and land use. The net carbon balance at any location is the result of multiple simultaneous losses and gains related to plant growth and organic matter decomposition (KM 8.1), historical and current LCLUC, and climate conditions including atmospheric carbon dioxide (CO_2) concentration and local rates of nitrogen deposition (Figure 6.6).[50] Northern Hemisphere forests are important carbon sinks (KM 7.1).[51] Boreal and tropical forests are both globally important carbon sinks, and since 1992 the boreal forest sink has been increasing in importance relative to the tropical forest sink.[52] Other ecosystems, such as grasslands,[53] wetlands,[54] and some agricultural systems (KM 11.1)[55] also contribute to the carbon sink, with complex and uncertain interactions with management actions.

Carbon Flux Response to Land-Cover and Land-Use Change



Changes in land cover and land use affect the fluxes of carbon taken up on land or released into the atmosphere, with impacts on these fluxes lasting for decades to centuries.

Figure 6.6. Land-cover or land-use changes can trigger complex sequences of carbon release and uptake. The example shown here illustrates a single idealized land-use event and the multiple impacts of such an event on carbon release and uptake fluxes. Net carbon flux from land use (red line) depends on time since disturbance, with climate change impacting all the component fluxes. Component fluxes include immediate losses from land clearance and fire (orange line), fast release of carbon from decomposition of forest products such as paper (blue-gray line), slow release from forest products such as lumber (brown line), and initial decomposition of litter and soil organic matter followed by carbon uptake during regrowth (dark gray line). The processes represented here typically span multiple decades to a century or more. In this illustration the net carbon flux (red line) eventually returns to zero, indicating that the influence of a single event has a finite period of impact on fluxes. During this period of impact, accumulated carbon losses (summed area of the red line above the zero flux level) can differ from accumulated carbon gains (summed area of the red line below the zero flux level), resulting in new steady states with either more or less total carbon storage than before the land-use event. Multiple events such as this can occur over time at a single location and can overlap each other in time, leading to even more complex patterns of fluxes. Figure credit: Oak Ridge National Laboratory.

While highly variable from year to year, the fraction of emissions taken up by land ecosystems has remained relatively stable on decadal timescales (Box 7.2). Recent evidence suggests that plant response to increasing atmospheric CO_2 is the dominant factor driving the land carbon sink at global scales.[56,57] A significant part of the land sink is also attributed to recovery following natural disturbances and legacy effects of past LCLUC.[58,59,60,61]

Intrinsic Value

Impacts of climate change are transforming landscapes in ways considered intrinsically detrimental. Communities with especially strong ties to place and local ecosystems, including but not limited to Tribal and Indigenous groups, may suffer declining cultural and spiritual connections with the land through these changes (KM 15.2),[62] such as through the drying of formerly perennial springs and streams that have spiritual significance[63] or through reduced opportunities for traditional harvesting of plants that decline as environmental conditions change. In central and northern Alaska, traditional methods of hunting on sea ice have become less feasible, and destabilization of thawing permafrost jeopardizes long-occupied communities (KM 29.3).[64,65] Subsistence and recreational fishing are reduced by ecosystem changes, some of which are climate driven and will worsen with additional warming;[66] for example, decreased salmon abundance has profound negative effects on many Tribes in the Northwest (KM 27.1).[67] Other recreational land uses are limited by the changing seasonality of river flows, loss of ice and snow, and loss of access to areas recently burned.

Key Message 6.2

Changes in Climate and Land Use Affect Land-System Resilience

Changes in climate and land use affect the resilience of land ecosystems and thus the fate of the services they provide (*high confidence*); for example, increasing drought reduces the ability of forests to store carbon. Climate and land-use change interact, and these interactions present challenges as well as opportunities for maintaining ecosystem resilience (*high confidence*).

The Value of Resilience

Ecosystem resilience—defined here as the capacity of a land system to respond to disturbance by resisting damage and/or recovering quickly, maintaining its essential structure and function—determines the persistence of services amid LCLUC. Disturbance is defined here as any discrete event (e.g., fire, flooding, drought, wind, geological hazard, pathogen, insect infestation, etc.) that occurs outside the range of natural variability (e.g., vegetation phenology, climate interannual variability, etc.) of the land system.[68] Management also impacts land systems, with the potential to both increase or decrease resilience. Resilience enables natural and built systems to maintain the continued delivery of goods and services in the face of changes. Climate change is affecting ecosystem resilience, triggering responses such as shifted distribution of species and reduced biodiversity (KM 8.2),[69,70] changed timing of biological processes,[71,72] altered success of existing land uses,[73,74] and lowered ability of systems to resist and recover from land-use activities and natural disturbance.[75] Ecosystems in the US have experienced increases in average temperature and extreme heat,[76] increased drought,[77] and increased intensity and frequency of extreme precipitation.[78,79] Changes in precipitation characteristics and warming have driven an increase in aridity in much of the United States,[80,81] with lasting impacts on ecosystems.[82] Land use and management affect ecosystem resilience and interact with climate change to determine the structure and function of the land system (KM 20.3).[83,84] The fact that human decisions can influence resilience provides opportunities for climate mitigation (Ch. 31) and adaptation (KM 6.3; Ch. 32) and is a foundation for nature-based solutions to climate change,[85] as well as an opportunity to improve resilience through management actions informed by Indigenous Knowledge (KM 16.2).[86]

Interactions Between Climate Change and the Land System and Effects on Resilience

Climate change and land use individually and interactively affect land systems, the services they provide to humans, and the resilience of ecosystems. Climate change alters landscape characteristics and management outcomes, which drive changes in land use and/or land cover (Figure 6.7). Land use itself impacts the land system, with potential to both increase and decrease resilience. Land use and land cover help determine climate via effects on carbon, water, and energy exchange with the atmosphere.

Climate change affects ecosystem resilience, structure, and function. For example, tree mortality events have resulted from drought and/or high temperatures in the temperate and boreal forests of western North America,[87,88] and widespread death of many tree species has been linked to climate change through wildfire and insect attack.[89,90] Warming-induced drought is causing widespread mortality of forests in the Southwest US.[91] Increased tree mortality and impaired regeneration decrease the resilience of forests (KM 7.1).[92,93]

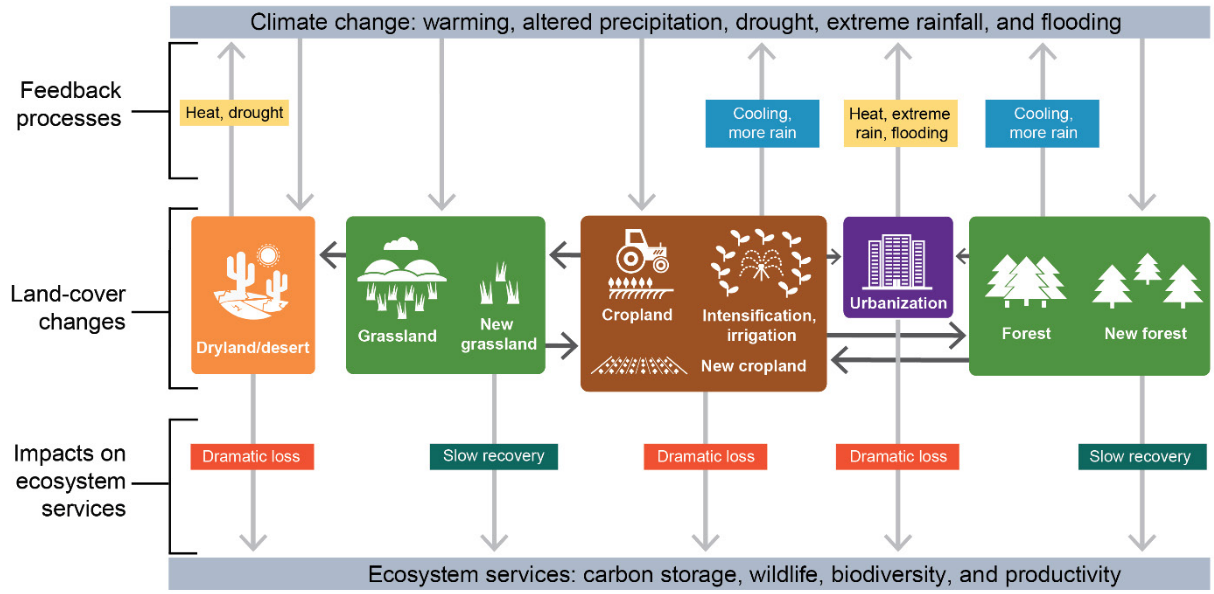
Increases in average temperature and altered precipitation patterns cause changes in species composition,[92,93] such as encroachment of shrubs into grasslands[94] and invasion by exotic grasses into rangelands, drylands, and forests.[41,95] Exotic grass invasion increases fuel loads and the ability of fire to move across the landscape, often resulting in large increases in fire risk.[41,96,97] By reducing fuel moisture, hotter and drier climates lengthen the wildfire season and lead to larger, more severe fires.[20,21] Increased wildfire frequency and severity can result in the loss of soil organic carbon through combustion[98] and postfire erosion.[24] In boreal systems, increased fire frequency may lead to changes in forest type,[99] while streamflow changes and permafrost thaw may trigger transition from peatland to forest.[100,101] Interactions between fire, climate change, and human development are multifaceted and include not only warming-induced increases in wildfire but also management actions to reduce wildfire fuel, the effects of fire on human populations, postfire recovery, and fire-induced changes in forest type (KM 8.1). Drought, wildfire, and unsustainable land-use practices cause land to lose productivity, which may trigger desertification in arid and semiarid regions.

Changes in land cover influence local and regional climate through both biogeochemical and biophysical pathways. The biogeochemical effects of vegetation loss, including both immediate CO_2 emissions and missed capacity for carbon sequestration (KM 6.1), have a warming impact at the planetary scale.[102] Vegetation loss causes immediate changes to local and regional climate through biophysical effects (e.g., Jiang et al. 2021;[103] Wang et al. 2016[104]), including exposed ground or snow (cooling the surface by reflecting more sunlight), reduced evapotranspiration (warming the surface and reducing moisture supply for rainfall), and a smoother surface (warming the surface by reducing heat loss to the atmosphere). The net impact of land-cover change on local climate depends on season, background climate, and vegetation type. Across the United States, forest disturbance or forest loss during the 2000s and 2010s caused a net local warming at both evergreen and deciduous sites in arid/semiarid, tropical, temperate, and boreal zones.[105,106] This occurred because warming from the loss of transpiration more than compensated for the cooling effects of the more reflective land surface following forest loss; exceptions were found during boreal winter at high latitudes where strong cooling resulted from high albedo of exposed snow.[105,107] Similarly, climate over forests is cooler than the surrounding croplands and urban areas, and the increase of forest cover following agricultural abandonment during 1920–1990 is connected to the observed cooling trend in the Southeast US.[108]

Indirect interactions also have impacts on US ecosystem resilience.[1,109] Land-use decisions that consider the interactions of climate change and management can maintain and promote ecosystem resilience.[83,110] For example, the thinning of some western forests that are experiencing drought increases the resilience of the forests to future trends of warming and drying.[111]

Changes in climate and land use offer opportunities for mitigation and adaptation, such as post-disturbance restoration of lands using climate-adapted species, which could increase biodiversity and resilience to climate change.[112] Increasing land-based carbon storage may be achieved by shifts in land management (KM 6.3), for example by afforestation (Ch. 7), altered grazing practices (Ch. 11),[53] modified crop management (Ch. 11), conserved agricultural lands,[113] active restoration of disturbed lands,[114] and the use of prescribed fire to avoid wildfire.[115]

Land, Climate Change, and Ecosystem Resilience



This figure shows the primary land-use and land-cover changes, their interactions with climate, and impact on ecosystems.

Figure 6.7. Land-use and land-cover changes interact with climate change, leading to lasting impacts on ecosystem services and resilience. Black arrows represent land conversions, and gray arrows represent impact or feedback processes supported by existing literature. Figure credit: University of Connecticut, USDA Forest Service, USGS, and Oak Ridge National Laboratory.

Land System Resilience Risks Associated with Increasing Development

Among all classes of land-cover change in the contiguous United States between 1985 and 2016, the largest net change in any class was an estimated gain of 50,660 square miles (131,209 km^2) of developed lands, at an average rate of 1,634 square miles (4,233 km^2) per year, primarily at the expense of forest and agricultural land,[116] a trend that continues to the present (Figure 6.4). Urban heat island effects exacerbate the impacts of warming on heat hazards, which disproportionately harm low-income communities (KM 12.2; Figure 12.6; App. 4). Warming-induced increases in precipitation extremes lead to higher flash flood risks, with especially devastating effects in urban regions where impervious surfaces cannot absorb rainwater. Although widespread increases in intense rain are evident,[117] river flooding trends are not consistently apparent across the US at present (KM 4.2);[118] however, in urbanized basins, as urban development expands, the size of flood peaks increases.[117,119,120] A resilient urban infrastructure, therefore, must be able to accommodate increased runoff from extreme storms (KM 12.2). Urbanization, through both urban land cover and increases in human-caused fine particulate matter, can alter atmospheric convection and precipitation, leading to stronger storms and more intense precipitation.[121,122,123,124] Urban heat islands reduce low clouds, which can increase plant water stress and possibly play a role in increasing wildfire risk, particularly in the wildland–urban interface.[125,126]

The adverse effects of urbanization on climate and ecosystems can be partly alleviated through sustainable practices designed to improve urban resilience. Urban greenspace (e.g., urban forest, farming, gardening) can mitigate the urban heat island effects and flooding risks[127,128,129] with varying degrees of effectiveness. While urban vegetation sequesters carbon during the growing season, the annual net carbon flux is uncertain.[130,131,132] Additionally, urban farming brings food security benefits, with yields comparable to conventional agricultural yields.[133]

Increasing energy demand, combined with new extraction technologies, has resulted in an average of 50,000 new oil and gas wells established per year throughout central North America since 2000.[134] Infrastructure for horizontal drilling and high-volume hydraulic fracturing has transformed millions of acres into industrialized landscapes, with reductions in ecosystem resilience, biodiversity, and the land carbon sink (e.g., Allred et al. 2015[134]). Reclamation of wells could become less successful with climate change.[135] The efficacy and resilience of renewable energy systems are expected to be affected by climate change in ways that will vary with generation type and location [136] and may strain the energy system (KMs 5.1, 5.2, 5.3).

Land System Resilience Risks Associated with Changes in Agriculture

After declining for multiple decades, cropland area in the United States increased at a rate of approximately 1,500 square miles (approximately 4,000 km^2) per year during 2008–2016 (Figure 6.4b),[137] attributable to increased domestic demand for corn ethanol and global demand for agricultural commodities as well as changes to conservation and crop insurance programs, interest rates, and possibly climate change–driven crop migration.[138,139] New croplands tend to occupy areas with marginal biophysical characteristics (e.g., erosive soils, nutrient deficiency, climatic stress) but displace grasslands and conservation easements that are higher-quality wildlife habitat than the remaining natural lands.[137] Expansion of agricultural area in the north-central United States has led to fragmentation of the remaining grassland, which limits the dispersal and population of native species (e.g., Wimberly et al. 2018[140]) and is expected to reduce ecosystem resilience. Conversion of grassland to cropland also contributes to carbon emissions from loss of soil organic carbon (KM 11.1).[141] The recovery of plant biodiversity, productivity, and soil carbon following agricultural abandonment is slow,[142] but the potential recovery of carbon in lands released from agricultural use is substantial, as has been shown by the large soil carbon gains made in land under the Conservation Reserve Program (KM 11.1).[113] Soil carbon increases, as well as increases in other ecosystem services, can be accelerated through activities such as deliberate revegetation with woody and herbaceous perennials.[143]

Agricultural extensification influences precipitation, with the direction of change depending on the region and the type of natural land cover prior to its conversion to cropland. For example, replacing grassland with cropland over the Great Plains can cause summer precipitation to increase.[144] Studies suggest that, in addition to increased area, intensification and irrigation are major causes of the observed increases in precipitation and decreases in temperature in the central US and Midwest[145,146,147,148]—changes that provide potentially more favorable conditions for crops and surrounding ecosystems. Land conversion to cropland without intensification was not associated with the observed cooling.[146]

Key Message 6.3

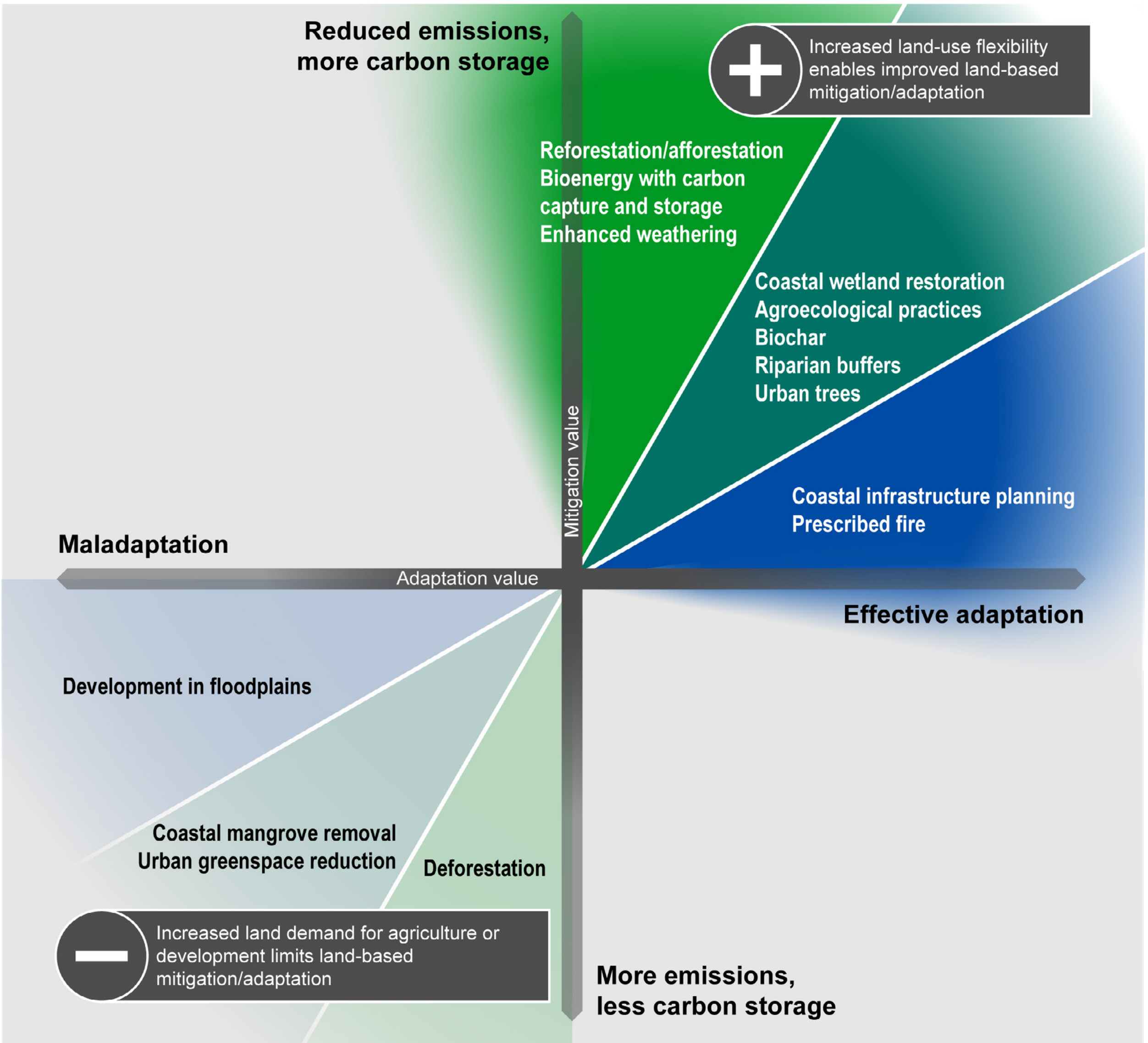
Mitigation and Adaptation Priorities Will Increasingly Constrain Future Land-Use Options

The future of land use in the United States will depend on how energy and agricultural technology evolves, how the climate changes, and the degree to which we prioritize climate mitigation and adaptation in land-use decisions (*high confidence*). US cropland area had been declining but has rebounded somewhat over the last 1–2 decades (*high confidence*). Future cropland needs will depend on uncertain factors such as agricultural technology improvements, dietary shifts, and climate change impacts (*medium confidence*). Decarbonization will require a continued expansion of solar and wind energy generation and transmission infrastructure (*very likely*, *high confidence*) and may involve large land-use changes toward land-based mitigation measures, including reforestation, other natural climate solutions, and bioenergy crops (*low confidence*).

Future Land-Use Scenarios

People value the ability to choose among multiple land-use options, although the ability to make these choices is not always experienced equitably across society (KM 20.3). There are increasing and competing demands for future land-use changes to support agriculture, housing, and infrastructure; to contribute to climate change mitigation and adaptation; and to conserve and possibly restore natural lands for biodiversity, resilience, and spiritual or recreational use. Scenario analysis is used to explore different climate mitigation "storylines," known as Shared Socioeconomic Pathways (SSPs; Table 3 in Guide to the Report), for how global land use, energy systems, and greenhouse gas emissions might evolve together under a set of standardized background driving forces such as changes in population, technology, and governance.[149,150] Land-use representation within the range of SSPs includes differences in land-use regulation, land productivity, trade, land-based mitigation and adaptation (Figure 6.8), and food/diet choices, along with a corresponding range of land-use trends that result from these drivers (Figure 6.9).

Mitigation and Adaptation Value of Future Land-Use Choices

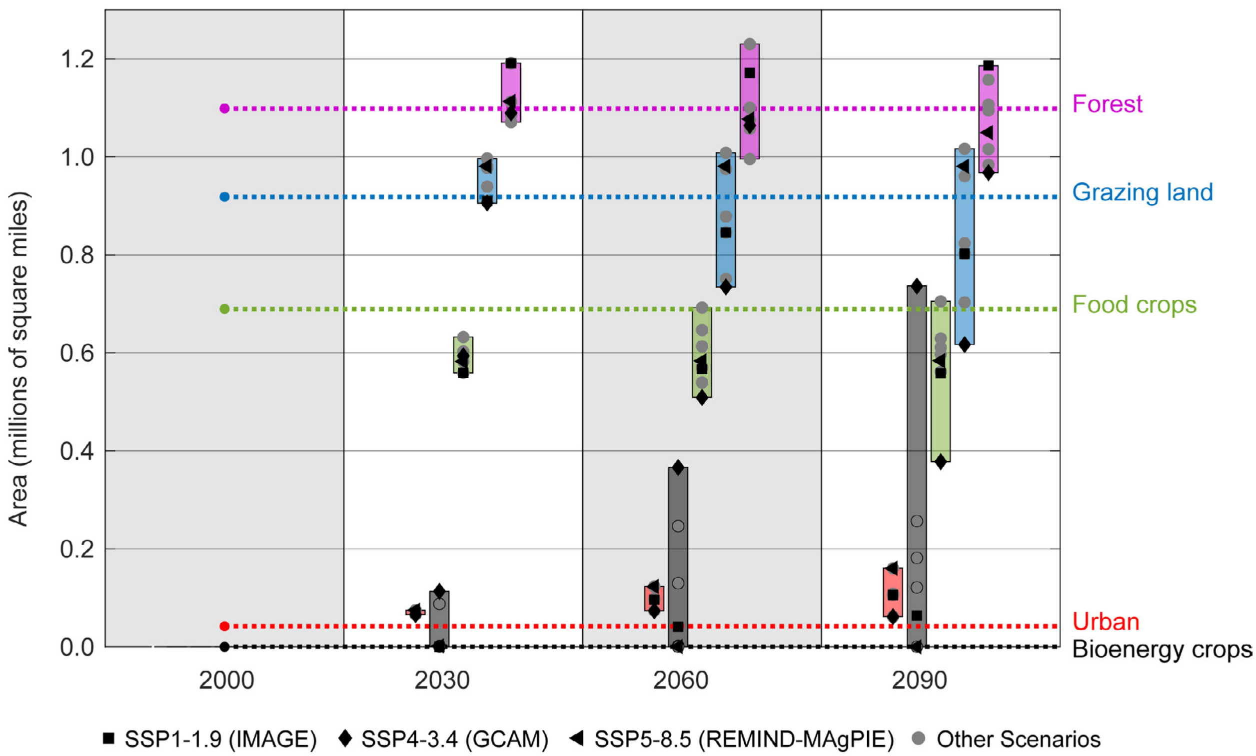


Future land-use choices have implications for climate mitigation and adaptation.

Figure 6.8. Future land-use choices can contribute to mitigating global climate change by reducing emissions or storing carbon (green), help individuals or communities adapt to the effects of global change (blue), or simultaneously support both mitigation and adaptation (green-blue), as shown in the upper-right quadrant. Flexibility in land use for mitigation and adaptation depends on background factors, including agricultural technology improvement, income growth, food waste reduction, and international cooperation. Alternately, indiscriminate land use change can lead to additional carbon emissions or maladaptation (lower-left quadrant). Many of these land-use choices are discussed elsewhere, including Key Messages 7.3 (forest adaptation), 9.3 (coastal adaptation), 11.1 (agricultural adaptation), and 12.3 (urban trees), as well as Box 32.2 (carbon dioxide removal). Figure credit: NASA, University of Maryland, and Oak Ridge National Laboratory.

Future land uses in the United States have been explored under several SSPs and at multiple spatial scales.[151] Future land use within the SSPs (Figure 6.9) is projected to involve substantial departures from historic trends (Figure 6.4), with determinants of change and resulting land-use patterns varying spatially and with time, based on multiple drivers including land management, demographic change, and ecological shifts (e.g., Richter and Bixler 2022 [152]). Many scenarios assume continued agricultural productivity increases, allowing the total area of cropland for food production to remain stable or decline despite the increasing global population.[150] Future land-use changes that limit global warming include reductions in grazing land associated with lower-animal-calorie diets and climate mitigation via reforestation or forest expansion. In addition, to offset fossil fuel use in other sectors, an often-dramatic expansion of bioenergy crops (producing nonedible plant material) is included in many scenarios. Large increases in urban area and reductions in forest area often accompany scenarios that involve greater levels of climate change.[153] Although these scenarios are useful for exploring different possible land-use futures at the aggregate scale, they do not quantify the likelihood of different land-use changes.

Scenario-Based Future Land-Use Trends



Future land-use scenarios describe a wide range of possible land-use changes in the United States.

Figure 6.9. Future land use in the 50 US states across eight different Shared Socioeconomic Pathways (SSPs) depicts increases in urban area, stability or decline in food crop area, and mixed outcomes for remaining land-use types, with large divergence among scenarios. (Data for the US-Affiliated Pacific Islands and US Caribbean are not included due to the spatial resolution of the underlying data source.) Colored bars show the range of land-use areas across all scenarios, and dashed lines indicate year 2000 values for comparison. Black symbols illustrate results for select scenarios of low emissions and high reforestation (SSP1-1.9 from the IMAGE model), moderate emissions with large nonedible bioenergy crop growth (SSP4-3.4 from the GCAM model), and high emissions (SSP5-8.5 from the REMIND-MAgPIE model), while gray symbols represent remaining scenarios. The large expansion of bioenergy crops is often taken from natural grasslands, which are not represented in this figure. Figure credit: University of Maryland, Oak Ridge National Laboratory, and NASA.

Future Agricultural Land Use

Flexibility in future land-use decision-making may be limited by agricultural land needs. Climate change is estimated to be slowing the rate of crop yield increases globally;[154,155] future land use will depend on the ability of the agricultural sector to adapt. Modeling results indicate that climate change–driven regional crop disruptions may emerge within 2–3 decades,[156] although such disruptions would be minimized with the adoption of adaptation and intensification measures such as supplemental irrigation and updated crop varieties.[157,158] There is also evidence of agricultural system adaptation through migration of crop cultivation ranges into more favorable climates in the United States and globally.[159]

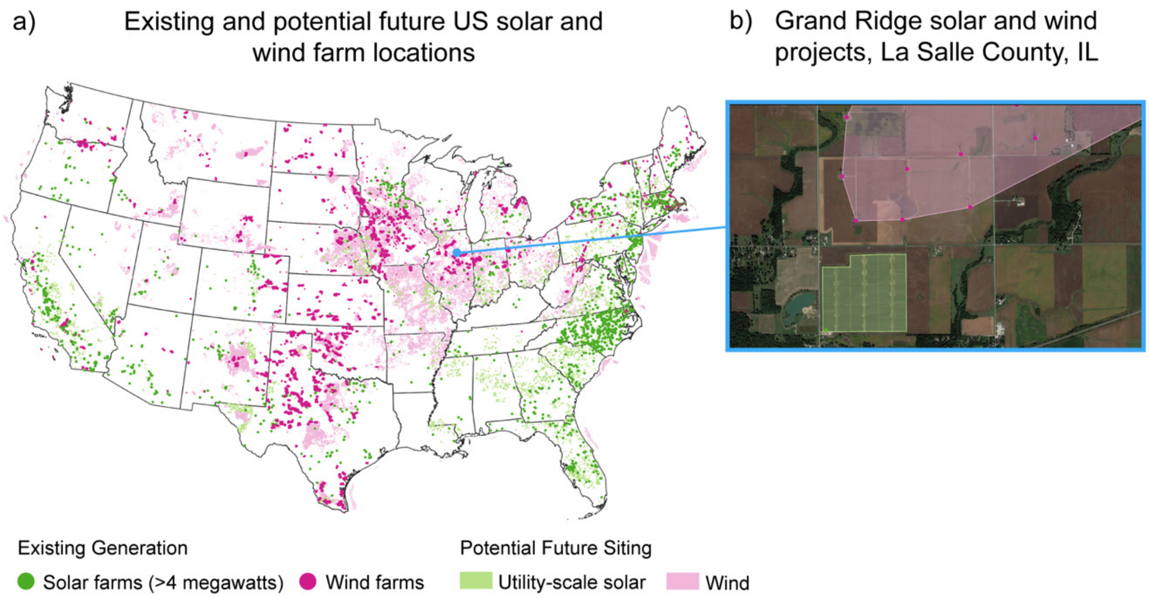
Individual farmers and landowners experience these changes in the context of increased variability in yields and income. As much as one-fifth of recent US crop insurance losses can be attributed to climate change.[160] Over time, adverse climate trends might affect the financial viability of current cropping practices and create pressure for individual producers to adopt adaptation practices (e.g., earlier planting dates, new crop varieties, modified tillage practices)[161] or switch crops. Such impacts will disproportionately affect small rural landholders (KM 11.3). Some regions are expected to see opportunities for new cropping systems[159,162] or for increasing the frequency of cropping on a given field.[163]

Future agricultural land requirements and associated climate feedbacks are sensitive to dietary choices and food waste.[164] American diets are high in meat consumption, a land-intensive food source, and universal adoption of USDA dietary guidelines would lead to a net reduction in the total biophysical land requirement for US agriculture.[165] Shifting toward diets even lower in animal products—potentially via novel plant-based meat substitutes[166]—could spare additional land and enable restoration of natural ecosystems.[167,168] US agricultural land futures could also be influenced by a continuation of the reduced household food waste observed during the COVID-19 period.[169,170]

Future Land Use for Mitigation

Mitigation scenarios that limit global warming to 1.5° or 2°C (2.7° or 3.6°F) above preindustrial levels imply large expansions of renewable energy production, electricity transmission, and land-based carbon mitigation (Ch. 32).[171] In scenarios of net-zero emissions by 2050, wind turbines may be visible across more than 130 million acres, an area greater than Colorado and Wyoming combined (Figure 6.10).[172] However, individual wind turbines have a small physical footprint, and can be sited in areas of intensive agriculture (Figure 6.11).[173] While solar farms are more land-intensive than wind- and fossil-derived electricity sources,[174] it may be possible to integrate them into agricultural landscapes in ways that preserve or even enhance agricultural production.[175] Decarbonizing energy systems will require a multifold expansion in global production of key metals and minerals,[176] although proposals to build new mines or expand existing mines in the United States have often faced intense local opposition.[177]

Possible Future Wind and Solar Power Siting



Reaching net-zero emissions will require many new wind and solar projects across the US.

Figure 6.10. Decarbonization will require an expanded physical and visual footprint of renewable power generation. Panel (**a**) shows current and possible future siting of wind and solar generation under a scenario that reaches net-zero emissions by 2050.[172] Panel (**b**) is a zoomed in view of the existing Grand Ridge wind and solar projects in La Salle County, Illinois and possible future siting zones. Green and pink dots show locations of existing solar and wind generation, respectively. Light green and light pink shading shows potential future siting of utility-scale solar and wind. Figure credit: Oak Ridge National Laboratory, with panel (b) background imagery © 2023 Landsat/Copernicus, Maxar Technologies, USDA/FPAC/GEO, map data © 2023 Google.

Wind Power in Agricultural Landscapes

Renewable energy generation can be sited in ways that minimize agricultural disruption.

Figure 6.11. While wind turbines may be visible over an area of more than 130 million acres under some net-zero scenarios,[172] the actual amount of land they physically occupy is much smaller. Photo credit: franckreporter/E+ via Getty Images.

The purposeful use of vegetation to capture or store additional carbon is one of the largest but most uncertain elements in future land-use projections. Many scenarios rely on land-based mitigation measures,[178] including land-intensive reforestation or carbon-negative bioenergy production to achieve carbon dioxide removal (CDR) from the atmosphere,[172,179,180] often implying unprecedented rates of land-use change.[181] Bioenergy is the most land-intensive form of renewable energy,[174] although it is valued in integrated assessment models for providing fuels for long-haul aviation and freight transport in addition to CDR (KM 32.3). Future bioenergy expansion may rely on dedicated cellulosic biomass crops cultivated on low-value land to minimize conflicts with existing agricultural production,[182,183] with positive or negative effects on ecosystem carbon storage depending on previous land use.[184]

Existing experience with land-based mitigation measures is limited, and the efficacy of forest carbon offsets, agricultural soil carbon enhancement, and first-generation biofuel programs remains controversial.[185,186,187,188] Most of the limited CDR achieved to date has come from forest restoration and management, and current CDR deployment plans fall far short of the scale envisioned in many decarbonization scenarios.[189] In the absence of such land-based mitigation measures, limiting global warming to below 1.5°C (2.7°F) will require even more aggressive emissions reductions[190] or breakthroughs in competing technologies such as direct air capture of CO_2.[191]

These mitigation trends imply new opportunities for landowners to generate additional revenues from leasing land for renewable energy generation or transmission, from government-run conservation payment programs, or from private carbon markets. However, these new opportunities also carry risks of conflict around conservation and the best use of public lands.

Broader Impacts of Land-Use Choices

Future land-use choices also include adaptations to climate change such as locating infrastructure away from potential hazards, strengthening natural ecosystems as buffers to climate extremes (e.g., coastal forests and wetlands), and planting trees in urban areas to reduce heat stress.[192] Many of these activities have mitigation co-benefits (e.g., urban trees also store carbon).[193] Efforts to reduce land use–driven habitat fragmentation are also expected to decrease the risks of disease transmission from animals or insects to humans, as well as pandemics.[194,195,196] All components of the food supply system are expected to be impacted by future land-use choices and climate change,[194] which will be felt unequally across society (KM 11.2). Land-use planning in the United States will be determined by many decision-makers, including land managers at federal, state, and local levels, as well as private and Tribal landowners, and achieving consensus over future land-use decisions is expected to be challenging.[197]

Traceable Accounts

Process Description

The chapter lead (CL) and coordinating lead author (CLA) developed a list of relevant topics and the expertise needed to represent those topics in the assessment process. The CL and CLA reviewed a list of nominated authors, which included information about affiliation and expertise. The CL and CLA identified potential chapter authors from that list based on their knowledge of the field, their expertise in the topical areas, and their contribution to the diversity of the author team in terms of affiliations, gender, and race. Invitations were sent and updated as necessary to adequately cover the needed expertise.

All meetings of the author team were virtual, except for the all-author meeting held in Washington, DC, in April 2023. Consensus was built during weekly meetings of the full author team, with candidate content developed by author sub-teams through additional weekly meetings. All authors participated in developing and conducting a public stakeholder engagement workshop, and all authors participated in reviewing and responding to public comments.

For development of candidate text for each Key Message, the authors discussed the key topics that should be addressed based on their assessment of the literature, expert knowledge, and input from agency and stakeholder meetings. The authors then assigned topics according to expertise and performed a literature review to evaluate and synthesize information regarding land use and land-cover change, climate change, and related ecosystem controls. Based on this review, they developed Key Messages, central points, and examples to communicate the issues, challenges, and opportunities related to land system goods and services, land system resilience, and future land-use options.

Key Message 6.1

The Goods and Services Provided by Land Systems Are Threatened by Climate Change

Description of Evidence Base

Land-cover and land-use datasets for the US are detailed and reliable when considering a relatively small number of land-cover types and land-cover or land-use transitions, although the best available data for different regions (contiguous US, Alaska, Hawai‘i, and Puerto Rico) cover slightly different time periods and use different though related methods.

There is consensus that more extreme rain will cause more landslides in a warmer climate, but the spatial distribution of anticipated future effects has not been resolved with much certainty; Gariano and Guzzetti (2016)[10] provided a synthesis of many studies that, in total, support these interpretations. Some individual mass-movement events have been attributed directly to climate change, but many landslides are caused more directly by factors without a clear link to a warming climate, such as slope oversteepening (by human construction) or local soil, bedrock, and hydrologic conditions. A broad literature base supports these inferences. The link between climate and slope-failure hazards, including the characteristics of rainfall, terrain, and burn severity that contribute to postfire debris flows (e.g., Kean et al. 2019[22]), is a rapidly growing research area.

The literature examining agricultural land practice and connections to climate change is broad and deep, covering many cropping and forestry practices in many regions across the US. There is a tendency for studies to focus more on small regions than on broad spatial patterns.

There is a long history of research into the connections between forest land cover and biodiversity, and this assessment drew on an extensive body of literature. These systems are complex, and the literature examines these connections from many perspectives.

While the topic of natural and managed carbon sinks on land is addressed by a large body of research, predictive understanding of interactions of the land carbon sink with land-use and land-cover change under a changing climate is still evolving (e.g., Zhu et al. 2018[61]).

Major Uncertainties and Research Gaps

Land-use and land-cover datasets with good temporal coverage and detailed spatial information are still lacking or highly uncertain for high-latitude regions such as Alaska. Additional observations and synthesis of ground-based and remotely sensed data would be required to fill these gaps.

Geographic variation in the two-way interactions between climate change and agricultural practice points to gaps in understanding of the detailed mechanisms connecting agricultural practices to long-term climate variation.

Relationships between agricultural practice, forestry practice, and climate change in mixed-management agroforestry systems have received less attention than traditional cropping or forestry practices. To the extent that strong mitigation measures place higher demand on mixed-use systems for both production and carbon sequestration, additional effort would be required to fill these research gaps.

Comprehensive assessment of the many component fluxes and processes contributing to net greenhouse gas fluxes due to land-use and land-cover change is still an important gap at scales larger than a few tens of square miles. Regional and continental-scale studies continue to rely on sparse observations and relatively simple assumptions about how different disturbance types, frequencies, and intensities interact with ecological communities of vegetation and soil biota to drive long-term net fluxes between land and atmosphere.

Description of Confidence and Likelihood

Based on strong and abundant empirical evidence, there is *high confidence* that climate change is increasing the regional intensity and frequency of extreme events, including rain, droughts, temperature highs, and fire. There is likewise a strong theoretical foundation for the attribution of these effects to human-caused climate change at present and further evidence that these effects will increase in the future as greenhouse gas concentrations rise. The empirical and theoretical basis for attributing changes in flood frequency and intensity is also robust, but not as strong as for extreme precipitation, droughts, and fire.[21,77] Based on abundant documentation, there is *high confidence* that these changes in weather and climate extremes cause risks to infrastructure, agriculture, ecosystems, and human health.

Broad empirical and theoretical understanding provides *high confidence* that wildfire is a major risk to the permanence of land carbon sinks, especially in woody ecosystems that have the potential to transition to savanna or grassland under increased fire frequency and/or severity. Other aspects of the net storage of carbon on land due to disturbances such as rotational forest harvest, windthrow, insect damage, and shifting agriculture are commonly identified as significant sources of uncertainty in estimating global or regional-scale carbon budgets.

Based on abundant documentation of climate change impacts on human–ecosystem interactions, there is *high confidence* that these impacts have negative consequences for subsistence, recreation, and spiritual practice. Some geographies and communities are more impacted than others, and fine-grained or predictive understanding of which communities and practices are most at risk is still being developed.

Key Message 6.2

Changes in Climate and Land Use Affect Land-System Resilience

Description of Evidence Base

The adverse impact of climate change (e.g., increased mean temperature, extreme heat, drought) on the resilience of land systems is supported by theory and observational studies involving a wide array of ecosystems, with overwhelming evidence in the United States coming from ecosystems that are increasingly influenced by drought, wildfire, and pests (e.g., Williams et al. 2019[21]). There is also strong evidence for how the loss of natural lands leads to degradation of ecosystem services that are slow to recover (e.g., Isbell et al. 2019[142]). However, the extent to which different ecosystems may recover or management choices are able to maintain or rebuild ecosystem resilience is not well known.

Globally, there is a large body of literature on how land-use and land-cover changes might influence local and regional climate, and findings are often region- and scale-dependent. This assessment focuses on studies over subregions of the United States, some based on observational data analysis and others based on numerical model experiments. Of the observation-based studies, some took a space-for-time approach by comparing climate trends over different land types (e.g., irrigated versus rainfed cropland, forest versus cropland; e.g., Mueller et al. 2016[146]), while others were based on observations before and after sudden land-cover changes (e.g., Li et al. 2022[106]). In numerical modeling studies, land-use or land-cover changes were imposed over a corresponding subregion (e.g., intensification or irrigation over cropland in the central US or Midwest, converting cropland to forest in the Southeast) with experiments designed to distinguish the impact of land-use change from the impact of greenhouse gas warming. These studies compared model results with observed climate trends to enable the attribution of observed climate phenomena to land-use practice or land-cover changes (e.g., Alter et al. 2018[145]). Findings from these studies are mostly consistent.

Warming-induced intensification of rainfall increases the nitrate leaching from cropping systems to surface water and groundwater, which exacerbates the environmental effects of increased fertilizer application. Different land-use practices (e.g., no-tillage management versus conventional tillage) may influence nitrate leaching, but the impact remains uncertain based on recent literature, which limits the extent of this chapter's assessment on this aspect.

A rich literature base supports the idea that while interactions between climate change, land use, land-cover change, and disturbance increase the risks of adverse impacts, they also provide multiple opportunities to reduce or lessen those impacts and ensure resilience.

Major Uncertainties and Research Gaps

The impact of urbanization on precipitation and other storms has been a topic of increasing research interest. Studies based on numerical modeling found a clear signal related to the enhancement of storm severity and precipitation (e.g., Debbage and Shepherd 2018[119]). However, observational data show a large degree of uncertainty and regional dependence. This is an important research gap.

Although geographically widespread increases in intense rain are evident, flooding trends are not consistently apparent at present.[118] Whether intense rain leads to flooding depends on soil type and land use, urban water-conveyance capacity, and how well the urban storm drainage system is maintained.

There are important uncertainties related to interactions between invasive species, disease, and natural disturbance. There is some evidence that changes in temperature and precipitation, as well as altered fire regimes, may negatively impact the competitive ability of native species, facilitating invasion by pests and pathogens (e.g., Ravi et al. 2022[41]). However, the outcomes are variable and seem to depend on multiple factors.

Research gaps and uncertainties also exist for the interactions of climate change with land-based renewable energy. Current research provides inconclusive results across the United States for all technologies.[136]

Description of Confidence and Likelihood

Based on a large literature base (e.g., Holden et al. 2018;[87] Stephens et al. 2018[93]), there is *high confidence* that climate change and climate change–related amplification of disturbance effects have a negative impact on ecosystem resilience.

Studies based on different methodologies (including observational data analyses and numerical model experiments) are consistent in suggesting that agricultural intensification and/or irrigation cause cooling and the increase of precipitation and atmospheric humidity in the central US during summer; similar climate effects were found in fall and winter resulting from the increase of forest cover in the southeastern US due to agricultural abandonment. Increased flooding was observed in urbanized basins (e.g., Hodgkins et al. 2019[120]); elsewhere, there is no clear signal of increased flooding risks despite the strong increase in extreme precipitation (frequency and intensity). Based on this understanding, there is *high confidence* that climate and land-use change interact and that these interactions present challenges as well as opportunities for maintaining ecosystem resilience.

Key Message 6.3

Mitigation and Adaptation Priorities Will Increasingly Constrain Future Land-Use Options

Description of Evidence Base

The evidence base describing Shared Socioeconomic Pathway (SSP) scenarios is large and well developed, having already been used in multiple international studies by the Intergovernmental Panel on Climate Change (e.g., IPCC 2022[180]) and the Coupled Model Intercomparison Project simulations. The "storylines" from the SSPs are developed by integrated assessment models (IAMs) into modeled projections of societal changes across multiple sectors. These scenarios provide alternative realizations of future societal pathways that are consistent with specified climate targets.[149,150] As such, they are useful for examining the range of possible challenges and changes facing our society over the rest of this century, although they do not provide predictions or probabilities of future trends.[198]

The Land-Use Harmonization 2 (LUH2) dataset provides a spatially explicit downscaling of the subset of SSP results used for the Scenario Model Intercomparison Project,[199] harmonizes them with historical land-use reconstructions, and provides a consistent data input for Earth system model simulations.[151] The LUH2 data provide global annual gridded (0.25° resolution) data of the fractional area occupied by 12 different land-use states, all transitions between those states, and land management data. The Land Change Monitoring, Assessment, and Projection (LCMAP) product described in the Introduction is a high-resolution annual land-cover dataset. That product complements the National Land Cover Database (NLCD),[200] which has greater thematic detail but is updated less frequently.

US agricultural land use in particular is tracked by a variety of surveys (e.g., the Census of Agriculture [CoA]) and longitudinal methods (e.g., the National Resources Inventory [NRI]), producing data that can be used to calibrate and validate the previously described remote sensing–based datasets.[8,137,201] Agricultural production is tracked through government statistics (e.g., the USDA National Agricultural Statistics Service), and crop yields are evaluated at finer spatial scales through crop insurance programs and combine yield monitors. The annual Inventory of US Greenhouse Gas Emissions and Sinks[55] estimates emissions from US land-use change, using agricultural area data from NRI and other sources.

Understanding of mitigation-driven land-use changes draws on the large IAM scenario evidence base described previously. Additionally, the Princeton Net-Zero America Project[172] is among the first to project where renewable electricity generation infrastructure might be sited at relatively fine spatial resolution.

Major Uncertainties and Research Gaps

Although human land-use activities have historically resulted in a net source of carbon emissions to the atmosphere, there is considerable uncertainty in these, and future, estimates.[202]

The SSP scenarios and harmonized land-use datasets are generated with a global focus. Although they can be analyzed and used for specific regional and national impacts, they are not likely to have US-specific levels of detail. In addition, the national-to-regional focus of these scenarios prevents the consideration of many societal equity and justice issues. Inequality and governance are included as drivers of land-use change in the SSPs, where they are used primarily to address inequality between countries and regions.[203] The SSP datasets used by LUH2 were each produced by a single IAM; it is possible that alternative IAMs would represent land-use differently within each SSP, and those potential differences were not explored here. There are also very few studies that provide short-term predictive forecasts of national-level land-use changes over the next 1–2 decades.[204] SSP scenario analyses do not include climate feedbacks to the future scenarios, but other studies using coupled human–climate models[205] show that climate change is expected to modify the future land-use choices society is able to, or desires to, make.

Future agricultural land requirements will depend on various difficult-to-assess factors such as changing dietary preferences and climate change effects on crop yields. While IAM studies typically assume that historically observed rates of crop yield increase will continue into the future, more detailed modeling efforts such as the Agricultural Model Intercomparison Project (AgMIP)[156] suggest that climate-driven reductions in corn yield in the western US may be clearly observable in as little as two decades under pessimistic emissions scenarios (SSP5-8.5), for example. The potential of in situ adaptation practices (e.g., adoption of different crop varieties or planting dates) to mitigate the severity of climate-driven disruptions is an active area of study, but the literature base on climate-driven shifts in crop cultivation range is still very limited.[159] Studies show that dietary shifts away from animal products toward plant products have a large biophysical potential for reducing total agricultural land use and supporting natural ecosystem restoration and land-based mitigation.[165,167,168] The SSP scenarios cover a range of dietary shift assumptions, including a shift toward low-meat diets in SSP1 and associated market and trade implications.[150]

The efficacy of existing land-based mitigation measures is often debated. For example, estimates of the mitigation value of US corn ethanol production diverge significantly[187,188] depending on assumed counterfactual land use in the absence of ethanol production and the degree to which diversion of finite arable land might lead to unintended agricultural expansion elsewhere. While remote sensing provides an invaluable tool for tracking deforestation, it can struggle to differentiate more subtle land-use changes with similar land cover (for example, unmanaged native grasslands, rangeland, pastureland, hay land, cropland–pasture, idled cropland, and conservation reserves), making it difficult to distinguish between permanent agricultural expansion versus transient agricultural intensification.[206] This ambiguity contributes to the debate around the viability and desirability of wide-scale land-based mitigation and carbon dioxide removal (CDR) measures in future decarbonization scenarios.

Description of Confidence and Likelihood

The land-use consequences of agricultural technology improvement (e.g., per-area crop yields, management intensity) and demand for land-based mitigation (including bioenergy and various CDR measures) are well explored in SSP scenario analyses.[150,205] Other collaborations (e.g., AgMIP) have explored the interaction between crop productivity and future climate change beyond what has been possible in integrated assessment modeling. Together, these literatures point to the influences of technology, mitigation needs, and climate change on land-use futures, hence the *high confidence* rating.

Primary data on cultivated cropland area and/or total cropland area are available via remote-sensing datasets (NLCD and LCMAP), longitudinal studies (NRI), and surveys (CoA). The longer-duration NRI and LCMAP datasets support a net decline in US cropland area over the last three and a half decades for which data are available, consistent with longer-term land-use records showing a mid-20th-century peak in US cropland area.[151] All four of these primary datasets are consistent with partial rebound of cropland area more recently, although with some disagreement around the starting year (as early as 2001 in NLCD or as late as 2012 in CoA) and magnitude of that rebound. Based on the agreement of these different primary data sources, there is *high confidence* of a long-term decline in US cropland area followed by a more recent rebound.

The LUH2 future scenarios all show stable or declining cropland use across the range of population growth and dietary shifts represented in the SSPs, although these scenario comparisons are not designed to represent the likelihood of different futures. Other literature suggests ongoing challenges in maintaining agricultural system resilience[155] in the face of a changing climate. Thus, continuation of the trend of declining land use is given a *medium confidence* rating, since there is not only evidence for multiple enabling preconditions but also key risks that are not captured in most scenario assessments.

The scenario assessment literature is consistent in identifying expanded electricity generation from renewable sources (i.e., wind and solar) and more widespread electrification of energy end use as preconditions for decarbonization of the energy sector.[171] This is consistent with recent trends of accelerating wind and energy deployment driven by the comparatively low cost of these energy sources, as well as policy support (e.g., through the Inflation Reduction Act), hence the *very likely*, *high confidence* rating. However, decarbonization scenarios have been widely criticized for over-reliance on land-intensive, technologically immature, or potentially unsustainable land-based mitigation and CDR measures,[207,208,209] and a variety of alternative scenarios that avoid land-intensive CDR have been developed.[190] Considering this, the statement about widespread land-use change for land-based mitigation is assigned a *low confidence* rating.

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