5 Land Cover and Land-Use Change

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5 Land Cover and Land-Use Change

Agricultural fields near the Ririe Reservoir, Bonneville, Idaho

Key Message 1

Land-Cover Changes Influence Weather and Climate

Changes in land cover continue to impact local- to global-scale weather and climate by altering the flow of energy, water, and greenhouse gases between the land and the atmosphere. Reforestation can foster localized cooling, while in urban areas, continued warming is expected to exacerbate urban heat island effects.

Key Message 2

Climate Impacts on Land and Ecosystems

Climate change affects land use and ecosystems. Climate change is expected to directly and indirectly impact land use and cover by altering disturbance patterns, species distributions, and the suitability of land for specific uses. The composition of the natural and human landscapes, and how society uses the land, affects the ability of the Nation's ecosystems to provide essential goods and services.

Executive Summary

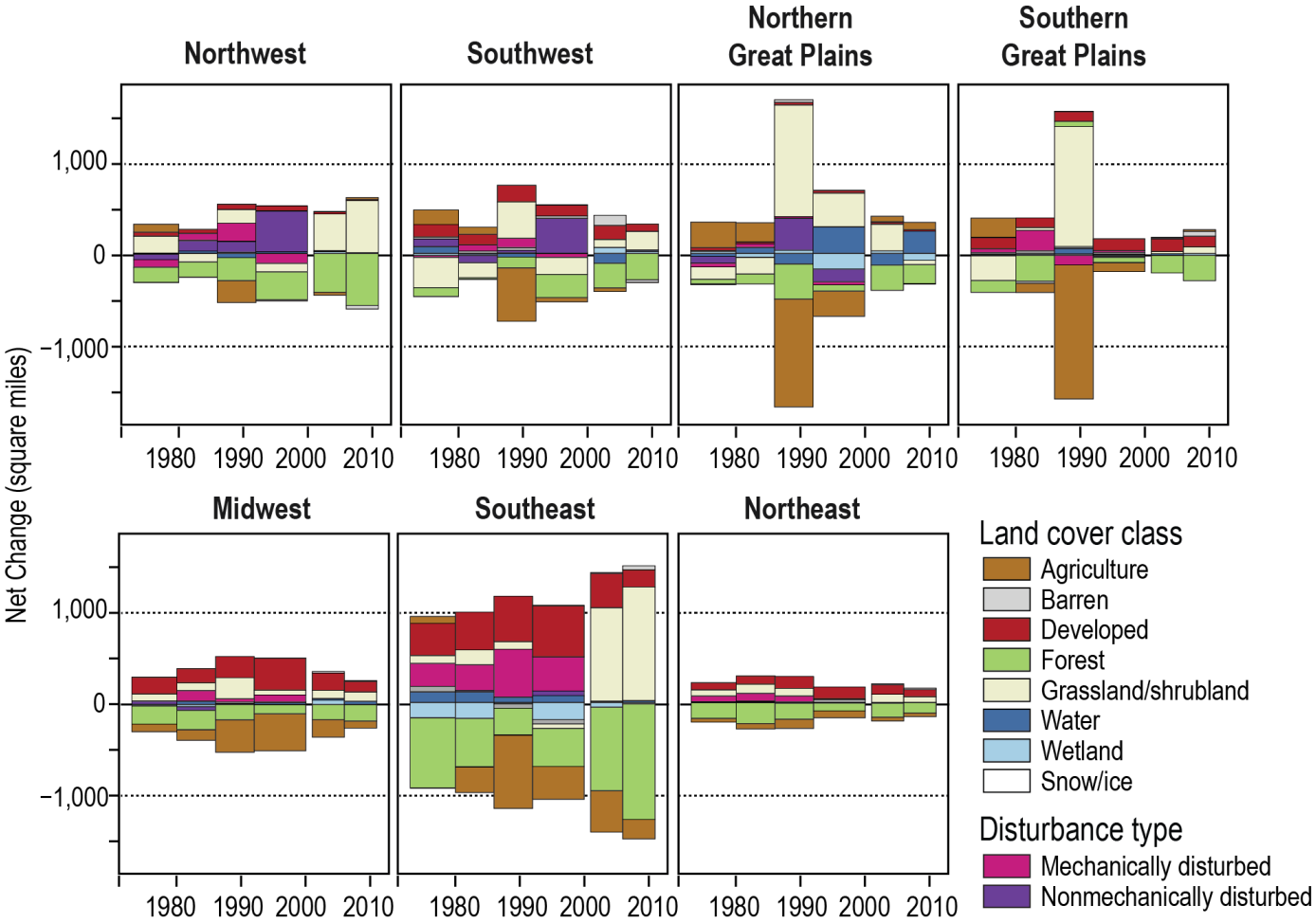
Climate can affect and be affected by changes in land cover (the physical features that cover the land such as trees or pavement) and land use (human management and activities on land, such as mining or recreation). A forest, for instance, would likely include tree cover but could also include areas of recent tree removals currently covered by open grass areas. Land cover and use are inherently coupled: changes in land-use practices can change land cover, and land cover enables specific land uses. Understanding how land cover, use, condition, and management vary in space and time is challenging.

Changes in land cover can occur in response to both human and climate drivers. For example, demand for new settlements often results in the permanent loss of natural and working lands, which can result in localized changes in weather patterns, temperature, and precipitation. Aggregated over large areas, these changes have the potential to influence Earth's climate by altering regional and global circulation patterns, changing the albedo (reflectivity) of Earth's surface, and changing the amount of carbon dioxide (CO_2) in the atmosphere. Conversely, climate change can also influence land cover, resulting in a loss of forest cover from climate-related increases in disturbances, the expansion of woody vegetation into grasslands, and the loss of beaches due to coastal erosion amplified by rises in sea level.

Land use is also changed by both human and climate drivers. Land-use decisions are traditionally based on short-term economic factors. Land-use changes are increasingly being influenced by distant forces due to the globalization of many markets. Land use can also change due to local, state, and national policies, such as programs designed to remove cultivation from highly erodible land to mitigate degradation,[1] legislation to address sea level rise in local comprehensive plans, or policies that reduce the rate of timber harvest on federal lands. Technological innovation has also influenced land-use change, with the expansion of cultivated lands from the development of irrigation technologies and, more recently, decreases in demand for agricultural land due to increases in crop productivity. The recent expansion of oil and gas extraction activities throughout large areas of the United States demonstrates how policy, economics, and technology can collectively influence and change land use and land cover.

Decisions about land use, cover, and management can help determine society's ability to mitigate and adapt to climate change.

Changes in Land Cover by Region



The figure shows the net change in land cover by class in square miles, from 1973 to 2011. Land-cover change has been highly dynamic over space, time, and sector, in response to a range of driving forces. Net change in land cover reveals the trajectory of a class over time. A dramatic example illustrated here is the large decline in agricultural lands in the two Great Plains regions beginning in the mid-1980s, which resulted in large part from the establishment of the Conservation Reserve Program. Over the same period, agriculture also declined in the Southwest region; however, the net decline was largely attributable to prolonged drought conditions, as opposed to changes in federal policy. Data for the period 1973–2000 are from Sleeter et al. (2013)[2] while data from 2001–2011 are from the National Land Cover Database (NLCD).[3] Note: the two disturbance categories used for the 1973–2000 data were not included in the NLCD data for 2001–2011 and largely represent conversions associated with harvest activities (mechanical disturbance) and wildfire (nonmechanical disturbance). Comparable data are unavailable for the U.S. Caribbean, Alaska, and Hawai‘i & U.S.-Affiliated Pacific Islands regions, precluding their representation in this figure. *From Figure 5.2 (Source: USGS).*

Introduction

Climate can affect and be affected by changes in land cover (the physical features that cover the land, such as trees or pavement) and land use (human management and activities on land, such as mining or recreation). A forest, for instance, would likely include tree cover but could also include areas of recent tree removals currently covered by open grass areas. Land cover and use are inherently coupled: changes in land-use practices can change land cover, and land cover enables specific land uses. Understanding how land cover, use, condition, and management vary in space and time is challenging, because while land cover and condition can be estimated using remote sensing techniques, land use and management typically require more local information, such as field inventories. Identifying, quantifying, and comparing estimates of land use and land cover are further complicated by factors such as consistency and the correct application of terminology and definitions, time, scale, data sources, and methods. While each approach may produce land-use or land-cover classifications, each method may provide different types of information at various scales, so choosing appropriate data sources and clearly defining what is being measured and reported are essential.

Changes in land cover can occur in response to both human and climate drivers. For example, the demand for new settlements often results in the permanent loss of natural and working lands, which can result in localized changes in weather patterns,[4,5] temperature,[6,7] and precipitation.[8] Aggregated over large areas, these changes have the potential to influence Earth's climate by altering regional and global circulation patterns,[9,10,11] changing the albedo (reflectivity) of Earth's surface,[12,13] and changing the amount of carbon dioxide (CO_2) in the atmosphere.[14,15] Conversely, climate change can also influence land cover, resulting in a loss of forest cover from climate-related increases in disturbances,[16,17,18] the expansion of woody vegetation into grasslands,[19] and the loss of coastal wetlands and beaches due to increased inundation and coastal erosion amplified by rises in sea level.[20]

Changes in land use can also occur in response to both human and climate drivers. Land-use decisions are often based on economic factors.[21,22,23] Land-use changes are increasingly being influenced by distant forces due to the globalization of many markets.[21,24,25,26] Land use can also change due to local, state, and national policies, such as programs designed to remove cultivation from highly erodible land to mitigate degradation,[1] legislation to address sea level rise in local comprehensive plans,[27] and policies that reduce the rate of timber harvest on federal lands[28,29] or promote the expansion of cultivated lands for energy production.[30] Technological innovation has also influenced land-use change, with the expansion of cultivated lands from the development of irrigation technologies[31,32] and, more recently, decreases in demand for agricultural land due to increases in crop productivity.[33] The recent expansion of oil and gas extraction activities throughout large areas of the United States demonstrates how policy, economics, and technology can collectively influence and change land use and land cover.[34]

Land use also responds to changes in climate and weather. For example, arable land (land that is suitable for growing crops) may be fallowed (left uncultivated) or abandoned completely during periods of episodic drought[35,36] or converted to open water during periods of above-normal precipitation.[37] Increased temperatures have also been shown to have a negative effect on agricultural yields (Ch. 10: Ag & Rural, KM 1).[38] Climate change can also have positive impacts on land use, such as increases

in the length of growing seasons, particularly in northern latitudes.[39,40,41] Forest land use is also susceptible to changes in weather and climate (Ch. 6: Forests). For example, the recent historical drought in California has resulted in a significant forest die-off event,[42,43] which has implications for commercial timber production. Similarly, insect outbreaks across large expanses of western North American forests have been linked to changes in weather and climate,[17] which in turn may result in important feedbacks on the climate system.[44] Sea level rise associated with climate change will likely require changes in coastal land use, as development and infrastructure are increasingly impacted by coastal flooding.[27,45,46,47] As sea levels rise, many coastal areas will likely experience increased frequency and duration of flooding events, and impacts may be felt in areas that have not experienced coastal flooding in the past (Ch. 8: Coastal, KM 1).

Decisions about land use, cover, and management can help determine society's ability to mitigate and adapt to climate change. Reducing atmospheric greenhouse gas (GHG) concentrations can, in part, be achieved by increasing the land-based carbon storage.[48] Increasing this carbon storage can be achieved by increasing the area of forests, stabilizing or increasing carbon stored in soils[49,50] and forests (Ch. 6: Forests),[51] avoiding the release of stored carbon due to disturbances (such as wildfire) through forest management practices (Ch. 6: Forests, KM 3),[52,53] and increasing the carbon stored in wood products.[54] However, there are large uncertainties about what choices will be made in the future and the net effects of the resulting changes in land use and land cover.[55,56,57]

State of the Sector

Humans have had a far-reaching impact on land cover within the contiguous United States. Of the approximately 3.1 million square miles of land area, approximately 28% has been significantly altered by humans for use as cultivated cropland and pastures (22%) or settlements (6%; Figure 5.1a).[3] Land uses associated with resource production (such as grazing, cropland, timber production, and mining) account for more than half of the land area of the contiguous United States,[58] followed by land that is conserved (16%), built-up areas (13%), and recreational land (10%; Figure 5.1b). Between 2001 and 2011, developed land cover increased by 5% and agriculture declined by 1%. Urbanization was greater between 2001 and 2006 than between 2006 and 2011, which may be attributable to the 2007–2009 economic recession.[59,60] The relative stability in agricultural land use between 2001 and 2011 masks widespread fluctuations brought about by the abandonment and expansion of agricultural lands (see Figure 5.2 for more detail).

Vegetated land cover, including grasslands, shrublands, forests, and wetlands, accounted for approximately two-thirds of the contiguous U.S. land area and experienced a net decline of approximately 5,150 square miles between 2001 and 2011. However, many of these areas are also used for the production of ecosystem goods and services, such as timber and grazing, which lead to changes in land cover but may not necessarily result in a land-use change. Between 2001 and 2011, forest land cover had the largest net decline of any class (25,730 square miles)[3] but forest land use increased by an estimated 3,200 square miles over a similar period (Ch. 6: Forests).[61] The increase in forest land use is due, in large part, to the conversion

Land-Use and Land-Cover Composition

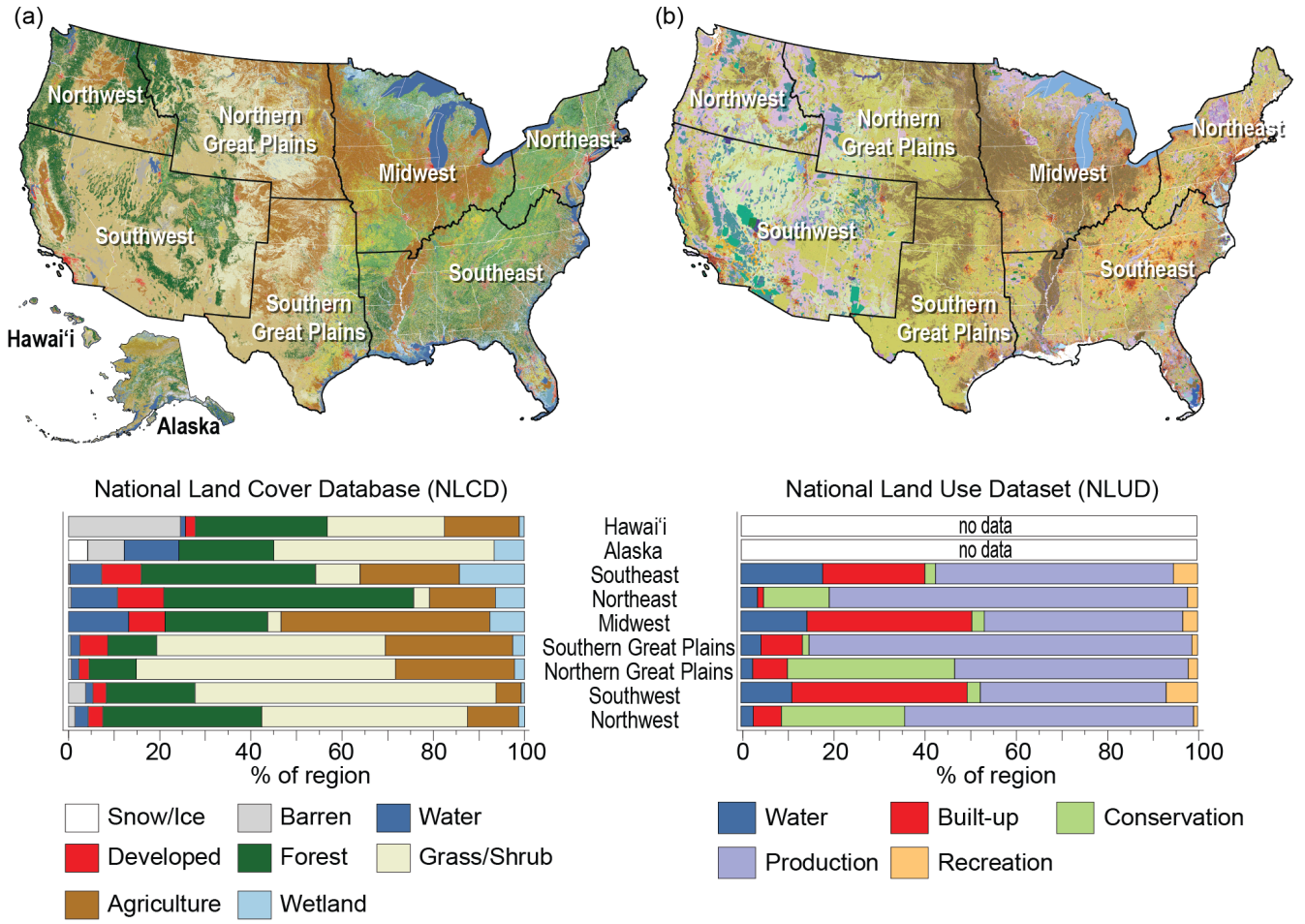


Figure 5.1: The composition of land use and land cover (LULC) is highly variable across the United States, owing in part to the natural environmental settings of each region. Forests dominate much of the vegetated areas of the eastern United States, while much of the Great Plains and Southwest are dominated by grasses and shrubs. Characterizing the composition of LULC also depends on the type of classification system used. This figure shows two different classification systems used to represent different components of land use and land cover: (a) the National Land Cover Database (NLCD),[3] which is derived from the classification of satellite images and represents the physical features on the ground, such as land that is covered by trees (forest cover) or impervious surfaces (developed cover); and (b) the National Land Use Dataset (NLUD),[58] which divides the land into 79 land-use categories that can be aggregated into five major use categories, including lands used for conservation, production of goods and services, and recreation. Data are unavailable for both the U.S. Caribbean region and the U.S.-Affiliated Pacific Islands in the NLCD and the NLUD. Source: USGS.

Estimates of Land-Use Area (Square Miles) by NCA Region

NCA Region	Croplands	Forestlands	Grasslands	Other Lands	Settlements	Wetlands
Alaska	111	133,438	305,659	76,388	558	64,336
Hawai'i	173	2,501	1,997	1,283	438	51
Midwest	212,994	142,314	43,753	4,140	36,638	18,867
Northern Great Plains	136,089	62,829	248,678	4,473	8,216	9,765
Northeast	24,490	131,383	11,649	2,929	24,856	12,521
Northwest	28,076	114,263	89,963	3,853	7,784	5,573
Southern Great Plains	103,698	103,325	182,216	2,547	19,878	7,790
Southeast	84,137	301,616	58,442	3,610	45,799	34,852
Southwest	39,782	174,669	416,464	30,324	22,311	10,237
Total	**629,550**	**1,166,338**	**1,358,821**	**129,547**	**166,478**	**163,992**

Table 5.1: Definitions of land use and land cover vary among agencies and entities collecting those data. This may lead to fundamental differences in these estimates that must be considered when comparing estimates of cover and use. For the purposes of this report, land cover is defined as the physical characteristics of land, such as trees or pavement, and land use is characterized by human management and activities on land, such as mining or recreation. The land-use area estimates in this table and throughout this chapter were obtained from the U.S. Forest Service's Forest Inventory and Analysis (FIA) Program and the National Resources Conservation Service's (NRCS) Natural Resources Inventory (NRI) data, when available for an area, because the surveys contain additional information on management, site conditions, crop types, biometric measurements, and other data that are needed to estimate carbon stock changes and nitrous oxide and methane emissions on those lands. If NRI and FIA data are not available for an area, however, then the NLCD product is used to represent the land use. Since all three data sources were used in the land representation analysis within the National Inventory Report, we used land-use estimates from the U.S. Environmental Protection Agency's annual greenhouse gas inventory report.[61] Data are unavailable for both the U.S. Caribbean region and the U.S.-Affiliated Pacific Islands in the NRI and FIA datasets.

of abandoned croplands to forestland[62] and the reversion to and expansion of trees in grassland ecosystems in the Great Plains and western United States.[61] There have also been losses in forest land use over the past 25 years, predominantly to grasslands and settlements, with grasslands and shrublands increasing in area by nearly 20,460 square miles. Collectively, non-vegetated areas, including water, barren areas, and snow and ice, account for approximately 6% of the total land area.

Coastal regions, as mapped within the National Oceanic and Atmospheric Administration's (NOAA) Coastal Change Analysis Program (C-CAP), account for 23% of the contiguous U.S. land area and have been particularly dynamic in terms of change, accounting for approximately 50% of all land-cover change and 43% of all urbanization in the contiguous United States. Approximately 8% of the coastal region changed between 1996 and 2010, which included about 16,500 square miles of forest loss and about 5,700 square miles of gain in urban land, a rate three times higher than that of the interior of the United States. Additionally, nearly 1,550 square miles of wetlands were lost in coastal regions, a trend counter to that of the Nation as a whole. A majority of this wetland loss has occurred in the northern Gulf of Mexico (Ch. 8: Coastal; Ch. 19: Southeast).[63] Coastal shoreline counties comprise approximately 10% of the United States in terms of land cover (excluding Alaska and the U.S. Caribbean) yet represent 39% of the U.S. population (2010 estimates), with population densities six times higher than in non-coastal areas.[64] Between 1970 and 2010, the population in coastal areas increased by nearly 40% and is projected to increase by an additional 10 million people over 2010–2020 (Figure 5.3).[64] Increases in the frequency of high tide

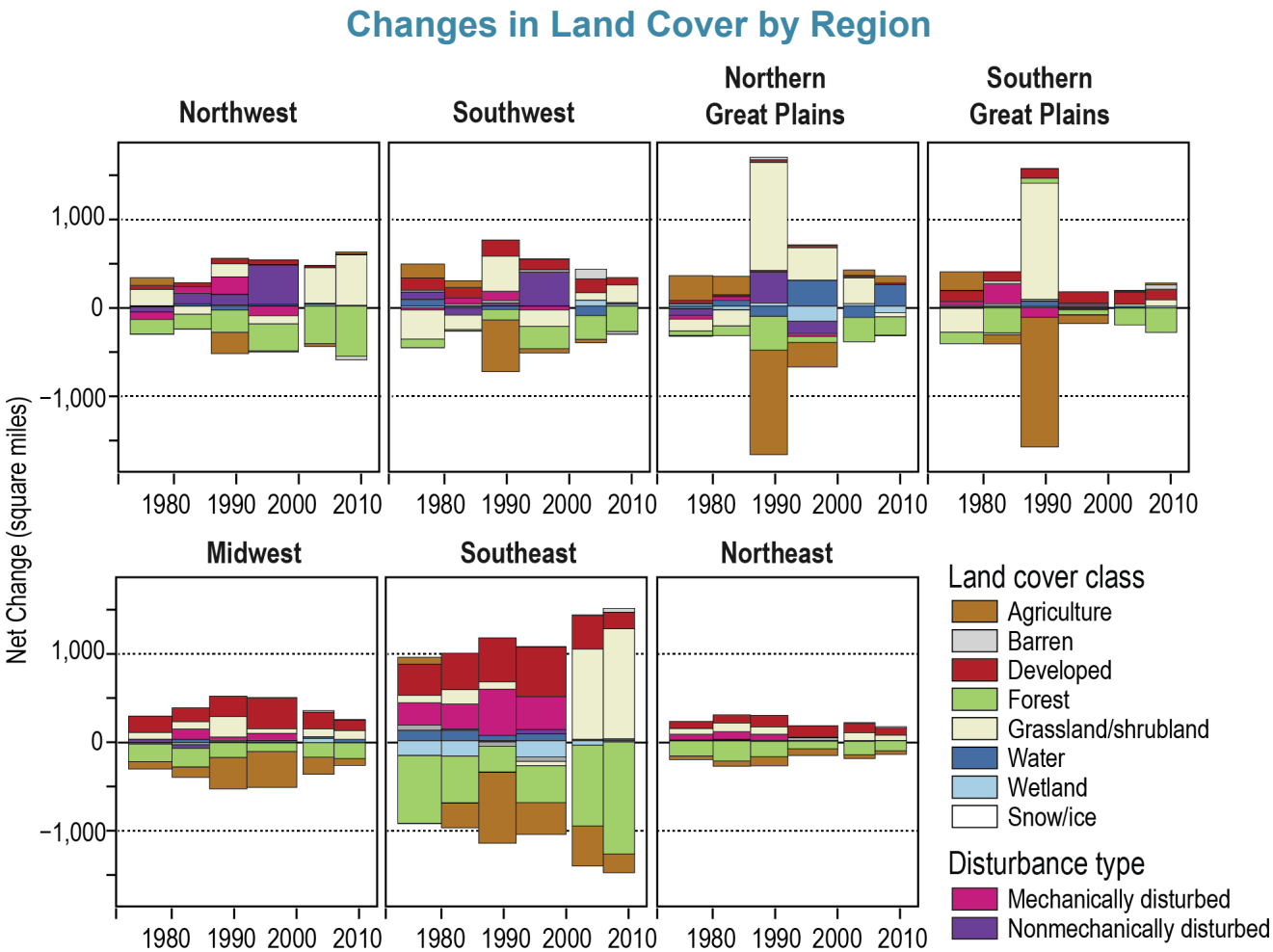


Figure 5.2: The figure shows the net change in land cover by class in square miles, from 1973 to 2011. Land-cover change has been highly dynamic over space, time, and sector, in response to a range of driving forces. Net change in land cover reveals the trajectory of a class over time. A dramatic example illustrated here is the large decline in agricultural lands in the two Great Plains regions beginning in the mid-1980s, which resulted in large part from the establishment of the Conservation Reserve Program. Over the same period, agriculture also declined in the Southwest region; however, the net decline was largely attributable to prolonged drought conditions, as opposed to changes in federal policy. Data for the period 1973–2000 are from Sleeter et al. (2013),[2] while data from 2001–2011 are from the National Land Cover Database (NLCD).[3] Note: the two disturbance categories used for the 1973–2000 data were not included in the NLCD data for 2001–2011 and largely represent conversions associated with harvest activities (mechanical disturbance) and wildfire (nonmechanical disturbance). Comparable data are unavailable for the U.S. Caribbean, Alaska, and Hawai'i & U.S.-Affiliated Pacific Islands regions, precluding their representation in this figure. Source: USGS.

flooding and extreme weather events (such as hurricanes and nor'easters), wetland loss, and beach loss from sea level rise present potential threats to people and property in the coastal zone (Ch. 8: Coastal, KM 1; Ch. 18: Northeast; Ch. 19: Southeast, KM 2).

Disturbance events (such as wildfire and timber harvest) are important factors that influence land cover. For example, forest disturbances can initiate a succession from forest to herbaceous grasslands to shrublands before forest reestablishment, with each successional stage having a different set of feedbacks with the climate. The length of an entire successional stage varies based on local environmental characteristics.[65] Permanent transitions to new cover types after a disturbance are also possible for many reasons, including the establishment of invasive or introduced species that are able to quickly establish and outcompete native vegetation.[66,67] Data from the North American Forest Dynamics dataset indicate that forest disturbances affected an

Development in the Houston Area

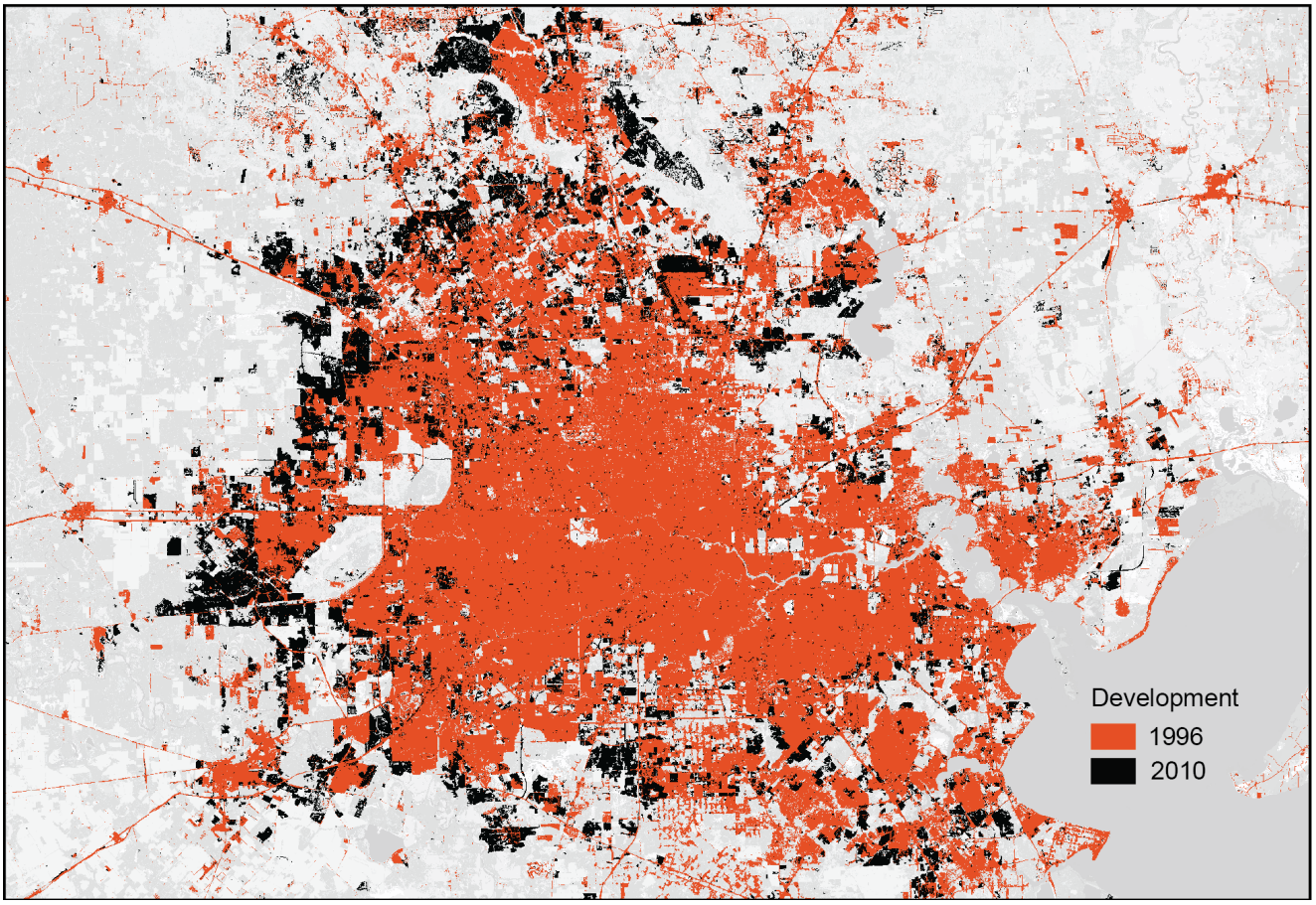


Figure 5.3: The figure shows the development-related changes surrounding Houston, Texas, from 1996 to 2010, as mapped by NOAA's Coastal Change and Analysis Program (C-CAP). Areas of change between 1996 and 2010 are shown in black.[63] These changes can have numerous impacts on the environment and populations, ranging from increased urban heat island effects and storm water runoff (the latter of which can increase flooding and produce water quality impacts), to decreases in natural cover. Source: USGS.

average of approximately 11,200 square miles per year in the contiguous United States from 1985 to 2010 (an area greater than the entire state of Massachusetts). Between 2006 and 2010, the rate of forest disturbance declined by about one-third.[68] Although these data include a wide range of disturbance agents, including fire, insects, storms, and harvest, the sharp decline likely corresponds to a reduction in timber harvest activities resulting from a drop in demand for construction materials following the 2007–2009 economic recession.

Wildland fires provide a good example of how ecosystem disturbance, climate change, and land management can interact. Between 1979 and 2013, the number of days with weather conditions conducive to fire has increased globally, including in the United States.[69] At the same time, human activities have expanded into areas of uninhabited forests, shrublands, and grasslands,[70] exposing these human activities to greater risk of property and life loss at this wildland–urban interface.[71,72] Over the last two decades, the amount of forest area burned and the expansion of human activity into forests and other wildland areas have increased.[73] These changes in climate and patterns of human activity have led in part to the development of a national strategy for wildland fire management for the United States. The strategy, published in 2014, was one outcome of the Federal Land Assistance, Management, and Enhancement (FLAME) Act of

2009. An important component of the national strategy[74] is a classification of U.S. counties based on their geographic context; fire history; amount of urban, forest, and range land; and other factors. The land-use, land-cover, and other components of the classification model are used to guide management actions.

Future Changes

Representative Concentration Pathways (RCPs) were developed to improve society's understanding of plausible climate and socioeconomic futures.[75] U.S. projections of land-use and land-cover change (LULCC) developed for the RCPs span a wide range of future climate conditions, including a higher scenario (RCP8.5)[76] and three mitigation scenarios (RCP2.6, RCP4.5, and RCP6.0) (for more on RCPs, see Front Matter and the Scenario Products section in App. 3).[77,78,79] Projected changes in land use within each scenario were harmonized with historical data[80] and include a broad range of assumptions, from aggressive afforestation (the establishment of a forest where there was no previous tree cover) in the Midwest and Southeast (RCP4.5) to large-scale expansion of agricultural lands to meet biofuel production levels (RCP2.6; see Hibbard et al. 2017 [81]).

The Shared Socioeconomic Pathways (SSPs) have been developed to explore how future scenarios of climate change interact with alternative scenarios of socioeconomic development (in terms of population, economic growth, and education) to understand climate change impacts, adaptation and mitigation, and vulnerability.[82,83] In a scenario with medium barriers to climate mitigation and adaptation (SSP2) and a scenario with high barriers to climate mitigation (SSP5), the amount of land devoted to developed use (for example, urban and suburban areas) is projected to increase by 50% and 80%, respectively, from 2010 levels by the year 2100. These changes represent a potential loss of between 500,000 and 620,000 square miles of agricultural or other vegetated lands (for more on SSPs, see the Scenario Products section of App. 3).[84]

Future changes in land use are likely to have far-reaching impacts on other sectors. For example, by mid-century, water use in California is projected to increase by 1.5 million acre-feet, driven almost entirely by a near 60% increase in developed water-use demand.[85] Research in Hawai'i projects a steady reduction in the strength of the state's annual ecosystem carbon sink, resulting primarily from a combination of urbanization and a shift toward drier, less productive ecosystems by mid-century.[86]

Key Message 1

Land-Cover Changes Influence Weather and Climate

Changes in land cover continue to impact local- to global-scale weather and climate by altering the flow of energy, water, and greenhouse gases between the land and the atmosphere. Reforestation can foster localized cooling, while in urban areas, continued warming is expected to exacerbate urban heat island effects.

The influence of land-use and land-cover change (LULCC) on climate and weather is complex, and specific effects depend on the type of change, the scale of the assessment (local, regional, or global), the size of the area under consideration, the aspect of climate and weather being evaluated (such as temperature, precipitation, or seasonal trends), and the region where the change occurs.[87,88]

Recent studies suggest that forests tend to be cooler than herbaceous croplands throughout much of the temperate region.[89,90,91,92,93,94,95,96]

These studies suggest that reforestation in the temperate forest region would promote cooling, with the magnitude of cooling decreasing with increasing latitude.[90,94,95,96,97] The scale of the cooling from reforestation would depend on its extent and location. Biogeophysical (albedo, surface roughness, and transpiration) changes arising from land-cover change tend to result in more localized changes, whereas biogeochemical changes (such as carbon sequestration) tend to have a more global reach. Reforestation in the temperate forest region is an effective climate mitigation and adaptation strategy.[90,94]

Fires in forests, grasslands, shrublands, and agricultural lands affect climate in two ways: 1) transporting carbon from the land to the atmosphere in the form of carbon dioxide and other greenhouse gases, and 2) increasing the concentration of small particles (aerosols) in the atmosphere that tend to reduce the amount of solar energy reaching the surface of Earth by increasing (although often temporarily) the reflectivity of the atmosphere.[98] Climate is also a principal determinant of an area's fire regime,[99] which refers to the pattern in which fires occur within ecosystems based on factors such as size, severity, and frequency. Studies suggest that most aspects of the fire regime are increasing in the United States (Ch. 6: Forests, KM 1; Ch. 26: Alaska).[18,99,100,101] However, the true extent of an altered fire regime's influence on climate is unclear, because the warming attributable to carbon releases to the atmosphere and decreases in surface albedo (at least temporarily) may be offset by increased reflectivity of the atmosphere from the increased concentration of small particles and the enhanced storage of carbon due to forest regrowth.[99]

Urban regions include several characteristics that can influence climate,[102] including construction materials that absorb more heat than vegetation and soils do, impervious cover that minimizes the cooling effect of evapotranspiration, the canyon-like architecture of buildings that tends to trap heat, and heat generation from vehicle and building emissions.[103,104] These factors make urban areas warmer than their surroundings, a phenomenon referred to as the urban heat island (UHI) effect. Urbanization has a small effect on global temperatures, with more dramatic effects evident regionally where urbanization is extensive.[105,106,107] The local-scale UHI impact is relative to the regional climate such that its effect tends to be more severe in the eastern United States and declines westward.[10,108,109,110,111] Although the evidence is not conclusive, urbanization may also increase downwind precipitation.[112,113,114] Further, climate change may act synergistically with future urbanization (that is, an increase in impervious cover), resulting in increased likelihoods and magnitudes of flood events (e.g., Hamdi et al. 2011, Huong and Pathirana 2013 [115,116]).

Water transport and application to cropland also impact climate. Between 2002 and 2007, irrigated lands expanded by approximately 1.3 million acres in the United States, with much of the change occurring in the Great Plains regions.[117] Approximately 88.5 million acre-feet of water were applied to approximately 55 million acres of irrigated agriculture in the United States in 2012.[118] Globally, the amount of water transported to the atmosphere through irrigated agriculture is roughly equivalent to the amount of water not transported to the atmosphere from deforestation.[119] Studies have shown reductions in surface air temperatures in the vicinity of irrigation due to both evaporation effects[120,121,122] and increases in downwind precipitation as a result of increased atmospheric moisture.[123] These potentially local-to-regional cooling effects are also counterbalanced by constraints on the availability of water for irrigation.[124]

Key Message 2

Climate Impacts on Land and Ecosystems

Climate change affects land use and ecosystems. Climate change is expected to directly and indirectly impact land use and cover by altering disturbance patterns, species distributions, and the suitability of land for specific uses. The composition of the natural and human landscapes, and how society uses the land, affects the ability of the Nation's ecosystems to provide essential goods and services.

Climate can drive changes in land cover and land use in several ways, including changes in the suitability of agriculture (Ch. 10: Ag & Rural),[125,126] increases in fire frequency and extent (Ch. 6: Forests),[18,101] the loss or migration of coastal wetlands,[127] and the spatial relocation of natural vegetation. The extent of the climate influence is often difficult to determine, given that changes occur within interconnected physical and socioeconomic systems, and there is a lack of comprehensive observational evidence to support the development of predictive models, leaving a large degree of uncertainty related to these future changes (Ch. 17: Complex Systems). Models can be used to demonstrate how climate change may impact the production of a given agricultural commodity and/or suggest a change in land use (for example, econometric models, global gridded crop models, and integrated assessment models). However, the true impact may be mitigated by the influence of global economic markets, a shift to a different crop that is better suited to the new climate pattern, technological innovations, policy incentives, or capital improvement projects. This area of integrated, multidisciplinary scientific research is just emerging.

Important feedbacks with agriculture are anticipated under changing climate conditions. Recent trends show a shift from dryland farming to irrigated agriculture throughout much of the Great Plains region (Ch. 22: N. Great Plains; Ch. 23: S. Great Plains).[117] Future projections suggest that cropland suitability may increase at higher latitudes[128] and that croplands could shift to livestock grazing southward.[126] For high-latitude regions, climate change could result in a large-scale transformation from naturally vegetated ecosystems to agronomy-dominated systems. Climate warming also could result in a shift from higher-productivity systems (such as irrigated agriculture) to lower-productivity systems (such as dryland farming).[129] Due to the globally interconnected nature of agricultural systems, climate change has broad implications for food security (Ch. 16: International).[130] Energy policies have also influenced the type and location of agricultural activities; for example, nearly two-thirds of recent land area converted for energy use was due to biofuel expansion[34,131] mandated by the Energy Independence and Security Act of 2007.[30,131] By 2040, the total new land area impacted by energy development could exceed an area the size of Texas—2,700 square miles per year,[34] which is more than two times higher than the historical rate of urbanization.[2]

Natural disturbances such as wildfires can trigger changes in land cover that have the potential to result in a permanent land-cover conversion. Over the past several decades, drought,[132] climate warming, and earlier spring snowmelt have led to an increase in fire activity across the United States (Ch. 6: Forests),[18,133] although the burnt area increase may be partly due to changes in fire suppression policies.[134] Under future warming scenarios (that is, A1B, as described here: http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=3), the burnt area in southwestern California could double by 2050 and increase by 35% in the

Sierra Nevada due to an increase in the length of the fire season and an increase in warmer and drier days.[135] Human activity will continue to play an important role in wildfire frequency and intensity. Hot spots of fire activity were identified at the wildland–urban interface,[136] and urbanization is expected to increase fire hazard exposure to people and property. Land management strategies, such as prescribed burning, fuel reduction and clearing, invasive species management, and forest thinning, have the potential to mitigate wildland fire and its associated consequences,[137] but more research is needed to evaluate their efficacy across a range of spatial and temporal scales.

Current relationships between plant species and climate variables[138] have been used to estimate potential changes in the geographic distribution of species and vegetation under future climate conditions.[12,139,140,141,142,143] Studies have projected the conversion of forests to shrubland and grassland across some areas of the western United States due to increasing aridity, pest outbreaks, and fire, resulting in a substantial transfer of carbon from the biosphere to the atmosphere.[144,145] For example, increases in mountainous forests and grasslands at the expense of alpine and subalpine communities have been projected.[146] Across North America, projected changes include an expansion of tropical dry deciduous forests and desert shrub/scrub biomes, a poleward migration of deciduous and boreal forests, and an expansion of grasslands at the expense of high-latitude taiga and tundra communities.[12,144,146,147,148,149] However, it is important to note that projecting the future distributions of vegetation and land cover is highly complex, driven not only by changes in climate but also land-use changes, shifts in disturbance regimes, interactions between species, and evolutionary changes.[150]

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Traceable Accounts

Process Description

Chapter authors developed the chapter through technical discussions, literature review, and expert deliberation via email and phone discussions. The authors considered feedback from the general public, the National Academies of Sciences, Engineering, and Medicine, and federal agencies. For additional information about the overall process for developing the report, see Appendix 1: Process.

The topic of land-use and land-cover change (LULCC) overlaps with numerous other national sectoral chapters (for example, Ch. 6: Forests; Ch. 10: Ag & Rural; Ch. 11: Urban) and is a fundamental characteristic of all regional chapters in this National Climate Assessment. This national sectoral chapter thus focuses on the dynamic interactions between land change and the climate system. The primary focus is to review our current understanding of land change and climate interactions by examining how land change drives changes in local- to global-scale weather and climate and how, in turn, the climate drives changes in land cover and land use through both biophysical and socioeconomic responses. Where possible, the literature cited in this chapter is specific to changes in the United States.

Key Message 1

Land-Cover Changes Influence Weather and Climate

Changes in land cover continue to impact local- to global-scale weather and climate by altering the flow of energy, water, and greenhouse gases between the land and the atmosphere (*high confidence*). Reforestation can foster localized cooling (*medium confidence*), while in urban areas, continued warming is expected to exacerbate urban heat island effects (*high confidence*).

Description of evidence

The Land-Use and Climate, IDentification of robust impacts (LUCID) project[88,151] evaluated climate response to LULCC using seven coupled land surface models (LSMs) and global climate models (GCMs) to determine effects that were larger than model variability and consistent across all seven models. Results showed significant discrepancies in the effect of LULCC (principally, the conversion of forest to cropland and grassland at temperate and higher latitudes) on near-surface air temperatures; the discrepancies were mainly attributable to the modeling of turbulent flux (sensible heat [the energy required to change temperature] and latent heat [the energy needed to change the phase of a substance, such as from a liquid to a gas]). Land surface models need to be subjected to more rigorous evaluations[151,152] and evaluate more than turbulent fluxes and net ecosystem exchange.[152] Rigorous evaluations should extend to the parameterization of albedo,[153] including the effect of canopy density on the albedo of snow-covered land;[154] the seasonal cycle of albedo related to the extent, timing, and persistence of snow;[155] and the benchmarking of the effect of present-day land cover change on albedo.[156] More recently, there is consistent modeling and empirical evidence that forests tend to be cooler than nearby croplands and grasslands.[91,92,93,95,96,156]

The study of the influence of wildland fire on climate is at its advent and lacks a significant knowledge base.[98,99] Improved understanding would require more research on the detection of fire characteristics;[157] fire emissions;[158] and the relative roles of greenhouse gas (GHG) emissions, aerosol emissions, and surface albedo changes in climate forcing.[98]

The urban heat island (UHI) is perhaps the most unambiguous documentation of anthropogenic modification of climate.[159] Two studies have found that the stunning rate of urbanization in China has led to regional warming,[105,106] which is consistent with the observation that land-use and land-cover changes must be extensive for their effects to be realized.[87] Research on the effects of urbanization on precipitation patterns has not produced consistent results.[113,114] Uncertainties related to the effect of urban areas on precipitation arise from the interactions among the UHI, increased surface roughness (for example, tall buildings), and increased aerosol concentrations.[160] In general, UHIs produce updrafts that lead to enhanced precipitation either in or downwind of urban areas, whereas urban surface roughness and urban aerosol concentrations can either further contribute to or dampen the updrafts that arise from the UHI.[160]

Major uncertainties

Land use and land cover are dynamic; therefore, climate is influenced by a constantly changing land surface. Considerable uncertainties are associated with land-cover and land-use monitoring and projection.[161,162,163,164] Land-cover maps can be derived from remote sensing approaches, but comprehensive approaches are typically characterized by coarse temporal resolution.[2,3,59,60] More recently, remote sensing has enabled annual classification over large areas (national and global), though these efforts have been centered on a single land cover or disturbance type.[68,165,166] Comprehensive multitemporal mapping of land use is even more limited and is a source of considerable uncertainty in understanding land change and feedbacks with the climate system. Deforestation, urbanization, wildland fire, and irrigated agriculture are the main land-use and land-cover changes that influence climate locally and regionally throughout the United States. Deforestation is likely to behave as a warming agent throughout most of the United States, but higher confidence in this finding would require more research on how to treat sensible and latent heat fluxes in coupled GCM–LSM models; the relationship of albedo to forest density in the presence of snow; the timing, persistence, and extent of snow cover; and real-world comparisons of the response of albedo to land-cover change. Urbanization constitutes a continued expansion of the UHI effect, increasing warming at local scales. Determining the effect of urbanization on precipitation patterns and storm tracks would require extensive, additional research. Tabular irrigation water volume estimates, such as those provided by the U.S. Department of Agriculture's (USDA) Farm and Ranch Irrigation Survey, must be translated into maps so that the data can be input in GCMs and LSMs to determine the impact of irrigation on climate. Current translation schemes do not provide consistent model output.[124] The effect of wildland fires on climate processes is an emerging issue for which there is little research. Fire releases carbon dioxide (CO_2) and other GHGs to the atmosphere, which, along with a decreased albedo, should promote warming. These warming effects, however, may be counterbalanced by the release of aerosols to the atmosphere and enhanced carbon sequestration by forest regrowth.[99]

Description of confidence and likelihood

There is *medium confidence* that deforestation throughout much of the continental United States promotes climate warming through a decrease in carbon sequestration and reduced transpiration. There is *low confidence* that wildland fires will impact climate, because many of the associated processes and characteristics produce counteracting effects. There is *high confidence* that urbanization produces local-scale climate change, but there is *low confidence* in its influence on precipitation patterns. There is *high confidence* that surface air temperature is reduced near areas of irrigated agriculture and *medium confidence* that downwind precipitation is increased.

Key Message 2

Climate Impacts on Land and Ecosystems

Climate change affects land use and ecosystems. Climate change is expected to directly and indirectly impact land use and cover by altering disturbance patterns (*medium confidence*), species distributions (*medium confidence*), and the suitability of land for specific uses (*low confidence*). The composition of the natural and human landscapes, and how society uses the land, affects the ability of the Nation's ecosystems to provide essential goods and services (*high confidence*).

Description of evidence

Much of the research assessing the impact of climate change on agriculture has been undertaken as part of the Agricultural Model Intercomparison and Improvement Project (AgMIP),[128] which has been understandably focused on productivity and food security.[128,129,167,168,169] Less effort has been devoted to understanding the impact of climate change on the spatial distribution of agriculture. Deryng et al. (2011)[170] used one of the AgMIP crop models (PEGASUS) to show poleward and westward shifts in areas devoted to corn, soybean, and wheat production. Parker and Abatzoglou (2016)[130] have reported a poleward migration of the USDA's cold hardiness zones as a result of a warming climate. Several empirical studies have found an increase in wildland fires in the western United States over the last several decades,[18,101,171] in which indicators of aridity correlate positively with the amount of area burned. Several studies have reported a decline in forest cover throughout the western United States and project future declines due to a warming climate and increasing aridity, as well as the concomitant likely increase in pest outbreaks and fire.[144,145,172,173,174] Several studies have also reported a poleward shift in the forest communities of the eastern United States, resulting primarily from CO_2 enrichment in a warming and wetter environment.[12,144,147,148,149,175]

Major uncertainties

Determining the impact of climate change on agriculture requires the integration of climate, crop, and economic models,[176] each with its own sources of uncertainty that can propagate through the three models. Sources of uncertainty include the response of crops to the intermingled factors of CO_2 fertilization, temperature, water, and nitrogen availability; species-specific responses; model parameterization; spatial location of irrigated areas; and other factors.[129,169,177] The projection of recent empirical fire–climate relationships[18,101,171] into the future introduces uncertainty, as the empirical results cannot account for future anthropogenic influences (for example, fire suppression management) and vegetation response to future fires.[171,178] Similarly, process-based models

must account for vegetation response to fire, uncertainty in precipitation predictions from climate models, and spatiotemporal nonuniformity in human interactions with fire and vegetation.[178] Many of the studies on climate-induced spatial migration of vegetation are based on dynamic global vegetation models, which are commonly based only on climate and soil inputs. These models aggregate species characteristics that are not uniform across all species represented and are generally lacking ecological processes that would influence a species' range shift.[179,180,181,182,183] Considerable uncertainties are associated with land-cover and land-use monitoring and projection.[161,162,163,164] Land-cover maps can be derived from remote sensing approaches; however, comprehensive approaches are typically characterized by coarse temporal resolution.[2,3,59,60] More recently, remote sensing has enabled annual classification over large areas (at national and global scales), but these efforts have been centered on a single land cover or disturbance type.[68,165,166] Comprehensive multitemporal mapping of land use is even more limited and is a source of considerable uncertainty in understanding land change and feedbacks with the climate system.

Description of confidence and likelihood

There is *high confidence* that climate change will contribute to changes in agricultural land use; however, there is *low confidence* in the direction and magnitude of change due to uncertainties in the capacity to adapt to climate change. There is *high confidence* that climate change will impact urbanization in coastal areas, where sea level rise will continue to have direct effects. There is *medium confidence* that climate change will alter natural disturbance regimes; however, land management activities, such as fire suppression strategies, are likely to be of equal or greater importance. There is *low confidence* that climate change will result in changes to land cover resulting from changes in species distribution environmental suitability.

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