10 Grasslands

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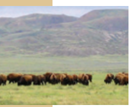


KEY FINDINGS

1. Total grassland carbon stocks in the conterminous United States, estimated to be about 7.4 petagrams of carbon (Pg C) in 2005, are projected to increase to about 8.2 Pg C by 2050. Although U.S. grasslands are expected to remain carbon sinks over this period, the uptake rate is projected to decline by about half. In the U.S. Great Plains, land-use and land-cover changes are expected to cause much of the change in carbon cycling as grasslands are converted to agricultural lands or to woody biomes (*medium confidence*).

2. Increasing temperatures and rising atmospheric carbon dioxide (CO_2) concentrations interact to increase productivity in northern North American grasslands, but this productivity response will be mediated by variable precipitation, soil moisture, and nutrient availability (*high confidence, very likely*).

3. Soil carbon in grasslands is likely to be moderately responsive to changes in climate over the next several decades. Field experiments in grasslands suggest that altered precipitation can increase soil carbon, while warming and elevated CO_2 may have only minimal effects despite altered productivity (*medium confidence, likely*).

4. Carbon stocks and net carbon uptake in grasslands can be maintained with appropriate land management including moderate levels of grazing. Fire suppression can lead to encroachment of woody vegetation and increasing carbon storage in mesic regions, at the expense of grassland vegetation (*high confidence, likely*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

10.1 Carbon Cycling in Grasslands

Grasslands cover 30% of North America and provide a wealth of essential ecosystem services, such as wildlife habitat, hydrological buffering, soil stabilization, carbon storage, and forage production. Grassland ecosystems are characterized by herbaceous vegetation, including grasses and nongrass species, with a minor component of woody vegetation in most regions. Most grasslands in North America are dominated by perennial vegetation, or species that continue growing for many years, although in parts of California and the Intermountain West, nonnative annual grasses now dominate. Grasses allocate 40% to 80% of net primary production (NPP) to roots (Hui and Jackson 2006), so most carbon storage takes place below ground (Silver et al., 2010; Smith et al., 2008; Soussana et al., 2004). Grasslands across North America occupy over 7 million km^2 (see Table 10.1, p. 401) and contain 10 to 90 megagrams of carbon (Mg C) per hectare in the top 20 cm of soil (Burke et al., 1989; Potter and Derner 2006; Silver et al., 2010).

Carbon storage, defined as the net uptake of carbon by a given pool or reservoir (IPCC 2013), can be quantified as the change in stocks measured over time, or as annual net ecosystem production (NEP), which can be measured as NPP minus losses from soil organic matter (SOM) decomposition (Chapin et al., 2006). NEP is also estimated from the sum of high-frequency net carbon dioxide (CO_2) exchange (NEE) measurements from eddy covariance "flux tower" methods. By contrast, net ecosystem carbon balance (NECB) accounts for all carbon uptake and loss processes, including harvest, natural disturbance, leaching, and trace gas species in addition to CO_2 (Chapin et al., 2006).

This chapter is relevant to both the Northern and Southern Plains National Climate Assessment regions, as well as the Southwest and Midwest regions. The spatial scope of this chapter encompasses the major North American grassland regions, which can be defined by climatic limitations. Grasslands occur where potential evaporation exceeds

Table 10.1. Average Modeled Net Ecosystem Production (In Tg C per Year During 2000 to 2006)

Country	Approximate Grassland Area (km^2)[a]	Inventory Analysis[b, c]	Atmospheric Inversion Models[c, d]	Land-Surface Models[c, d]
Canada	3,920,000	–3.06	–51.2	–29.3
United States	2,580,000	–13.2	–266.2	–104.8
Mexico	760,000	–9.06	–15.1	+3.6
North America	7,260,000	–25.2	–332.5	–130.5

This table, adapted from Hayes et al. (2012), presents three different approaches for estimating net ecosystem production (NEP): inventory analysis, atmospheric inversion models, and land-surface models.

Notes

a) Approximate grassland area is derived from www.statista.com/statistics/201761/projection-for-total-us-grassland-area-from-2010.

b) Inventory analysis estimates, in teragrams of carbon (Tg C) per year, are the sum of livestock methane (CH_4) emissions, livestock carbon dioxide (CO_2) emissions, and grassland net ecosystem exchange (NEE) for Canada and the United States. For Mexico, the NEP value for "Others" was used from Table S10 in Hayes et al. (2012).

c) A negative flux represents net ecosystem carbon uptake, while a positive flux indicates carbon loss from the ecosystem.

d) Atmospheric inversion models and land-surface models are from Table 2 in Hayes et al. (2012) and exclude CH_4 emissions and human settlement emissions.

precipitation, such as in central North America from Canada through Mexico and in mountain rain shadows in the western United States (Sims and Risser 2000). They also occur in more mesic (wet) regions where disturbance, management, or soil conditions prevent woody growth, such as in central Florida (Stephenson 2011). North American grasslands generally increase in productivity and carbon storage as precipitation increases, from west to east (Sims and Risser 2000). This pattern is observed in Canada and to a lesser extent in Mexico. Mixed-grass prairie is extensive in south-central Canada, while more arid desert grassland and shortgrass steppe extend through the southwestern United States into Mexico (Sims and Risser 2000). Grasslands at the more arid extreme are considered more vulnerable to diminished productivity in a future warmer climate (Hufkens et al., 2016), whereas grasslands in more mesic climates may be vulnerable to woody encroachment (Knapp et al., 2008a).

Land management strongly affects productivity and carbon cycling in grasslands (see Figure 10.1, p. 402). In the conterminous United States, grasslands, shrublands, rangelands, and pastures make up at least 40% of land cover (Reeves and Mitchell 2012; see Figure 10.1). Most areas of highly productive grasslands have been converted to agriculture (see Ch. 5: Agriculture, p. 229, for more details; Bachelet et al., 2017).

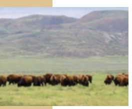
10.2 Current Understanding of Grassland Productivity and Carbon Stocks

10.2.1 Grassland Carbon Stocks and Fluxes

Key Finding 1 is based on estimates of carbon stocks and fluxes as determined by upscaling inventories with remote-sensing products and modeling approaches. This section of the chapter describes the current understanding of carbon stocks and fluxes, and later sections evaluate the processes responsible for changes in these pools and fluxes.

Continental Scale

Terrestrial biosphere models are important tools for understanding how the carbon cycle responds



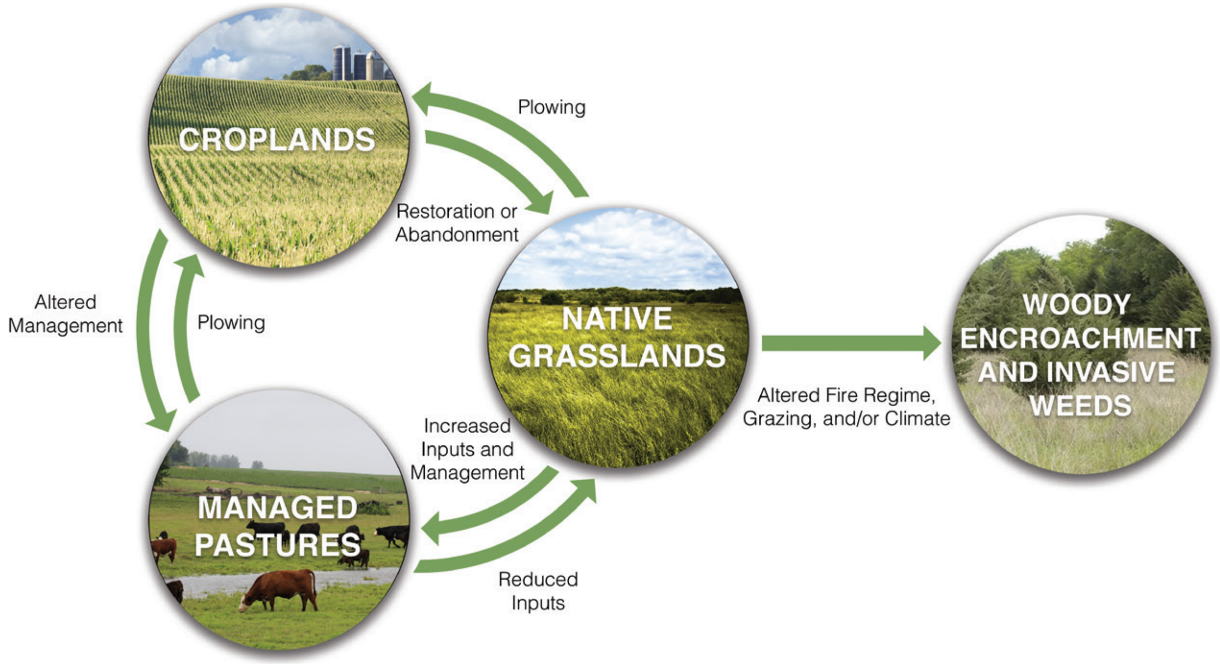


Figure 10.1. Management Activities and Their Effects on Grassland Carbon Cycling. Reduced fire frequency in mesic native grassland has allowed woody vegetation such as *Juniperus virginia* to expand and has been associated with rapid increases in carbon stocks in vegetation and soils (McKinley and Blair 2008). Other observed management impacts include lower carbon density in agricultural lands compared with grasslands (Zhu et al., 2011) and the rapid accumulation of soil carbon in intensively managed pastures in the southeastern United States (Machmuller et al., 2015). In addition, the rate of carbon uptake by croplands in the Great Plains is 30% lower than that of grasslands (Wylie et al., 2016).

to changes in climate, nutrient availability, and land use. Modeled rates of uptake or loss are dependent on a given region's processes and area. A multimodel synthesis study estimated that North American grassland acted as a carbon sink, with an average uptake rate of 38 grams of carbon (g C) per m^2 per year during the first 5 years of this century (Raczka et al., 2013). A similar synthesis of 17 land-surface models (LSMs) showed that North American grasslands acted as carbon sinks (see Table 10.1, p. 401) from 2000 to 2006 (Hayes et al., 2012). Atmospheric inversion models (AIMs) also predicted a carbon sink for North American grasslands but at a rate roughly twice the magnitude compared to that in land-surface models (see Table 10.1, p. 401; Hayes et al., 2012). At the national level, carbon sinks are proportional to the area in grasslands and reflect different management and climate conditions. U.S. grasslands contribute the continent's largest sink, followed by those in Canada, with Mexican grasslands approaching carbon-neutral status.

Similar to the modeled estimates, inventory analyses also suggest that Canadian and U.S. grasslands are carbon sinks (see Table 10.1, p. 401; Hayes et al., 2012). The differences in estimated carbon sink magnitude between these approaches could stem from estimating fluxes using changes in stocks (i.e., inventory methods) versus changes in atmospheric CO_2 concentrations (i.e., AIMs) or carbon cycle processes (i.e., LSMs), or from extrapolating fluxes over different land areas. Furthermore, most previous LSMs have not considered effects of land-use change and fire suppression, both which are implicit in AIM analyses. Inventories might miss these

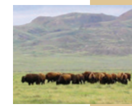


Table 10.2. Carbon Fluxes and Stocks for Grasslands and Shrublands in the Conterminous United States (Summarized from the LandCarbon Project, landcarbon.org/categories)

	Time Period	Biomass[a]	Soil[b]	Other[c]	Total	Area (10^6 km^2)
Annual Flux (Tg C per Year)[d]						
	2000–2005	+7.2	–45.5	–16.3	–54.7	2.66
	2005–2050	+5.8	–20.1	–7.6	–21.8	2.51
Total Carbon Stock (Tg C)[d]						
	2005	1,362.1	5,090.4	958.6	7,411.1	2.66
	2050	1,090.4	6,021.8	1,072.3	8,184.5	2.51

Notes

a) Biomass includes aboveground and belowground live plant parts.

b) Soil stocks consider the top 20 cm.

c) Other includes leaf litter and woody debris.

d) Values, in teragrams of carbon (Tg C), are averages of the A1B, A2, and B1 climate scenarios and estimated using the FORE-casting SCEnarios of land-use change (FORE-SCE) model and the Erosion-Deposition-Carbon-Model (EDCM), CENTURY, and PBN carbon models (Liu et al., 2012b, 2014; Zhu et al., 2011). A negative carbon flux represents net ecosystem carbon uptake, while a positive carbon flux indicates carbon loss from the ecosystem.

effects if they consider only areas that remain as grasslands. Recent LSM simulations indicate that fire suppression reduces areal extent of grasslands in the conterminous United States and allows woody biomass to encroach (Bachelet et al., 2017). A recently developed remote-sensing method discovered 300% more burned areas in the Great Plains than did the previous method for the 1984 to 2013 period (Hawbaker 2017). These examples demonstrate that considering disturbance and land-use effects is key to reducing uncertainties in inventories and model projections of carbon cycling. Section 10.5, p. 415, discusses these societal impact questions in more detail.

Conterminous United States

Various efforts on scaling up flux tower observations and biogeochemical modeling mostly confirm that U.S. grasslands typically have been a carbon sink in recent years (Liu et al., 2012b, 2014; Xiao et al., 2014; Zhang et al., 2011; Zhu et al., 2011). By scaling up flux tower observations, Zhang et al. (2011) showed that the Great Plains, which makes up the majority of U.S. grasslands, was a net sink from 2000 to 2008, with an average net uptake of 24 ± 14 g C per m^2 per year (i.e., annual uptake varied from 0.3 to 47.7 g C per m^2 per year). The result was consistent with a similar study over North America that showed U.S. grasslands were a net carbon sink from 2001 to 2012 (Xiao et al., 2014). However, a recent biogeochemical modeling study suggested that U.S. grasslands during 2001 to 2005 lost 3 teragrams of carbon (Tg C) per year, amounting to about 120 g C per m^2 averaged over the conterminous United States (Wang et al., 2015). These contrasting results, along with the differences shown in Table 10.1, p. 401, indicate a discrepancy between modeling estimates and empirical, data-driven values that contribute to uncertainty in grassland carbon cycling rates.

The LandCarbon project (www2.usgs.gov/climate_landuse/land_carbon) provided a national ecosystem carbon sequestration assessment conducted by the U.S. Geological Survey (USGS) in response to requirements of the Energy Independence and Security Act of 2007 (EISA; H.R. 6 — 110th Congress 2007). The objective of the EISA assessment was to evaluate policy-relevant carbon sequestration capacity in terrestrial ecosystems through management or restoration activities. Climate, land-cover change, and fire disturbance were included in the carbon assessment. Grassland and shrubland assessments were combined for this chapter. U.S. national

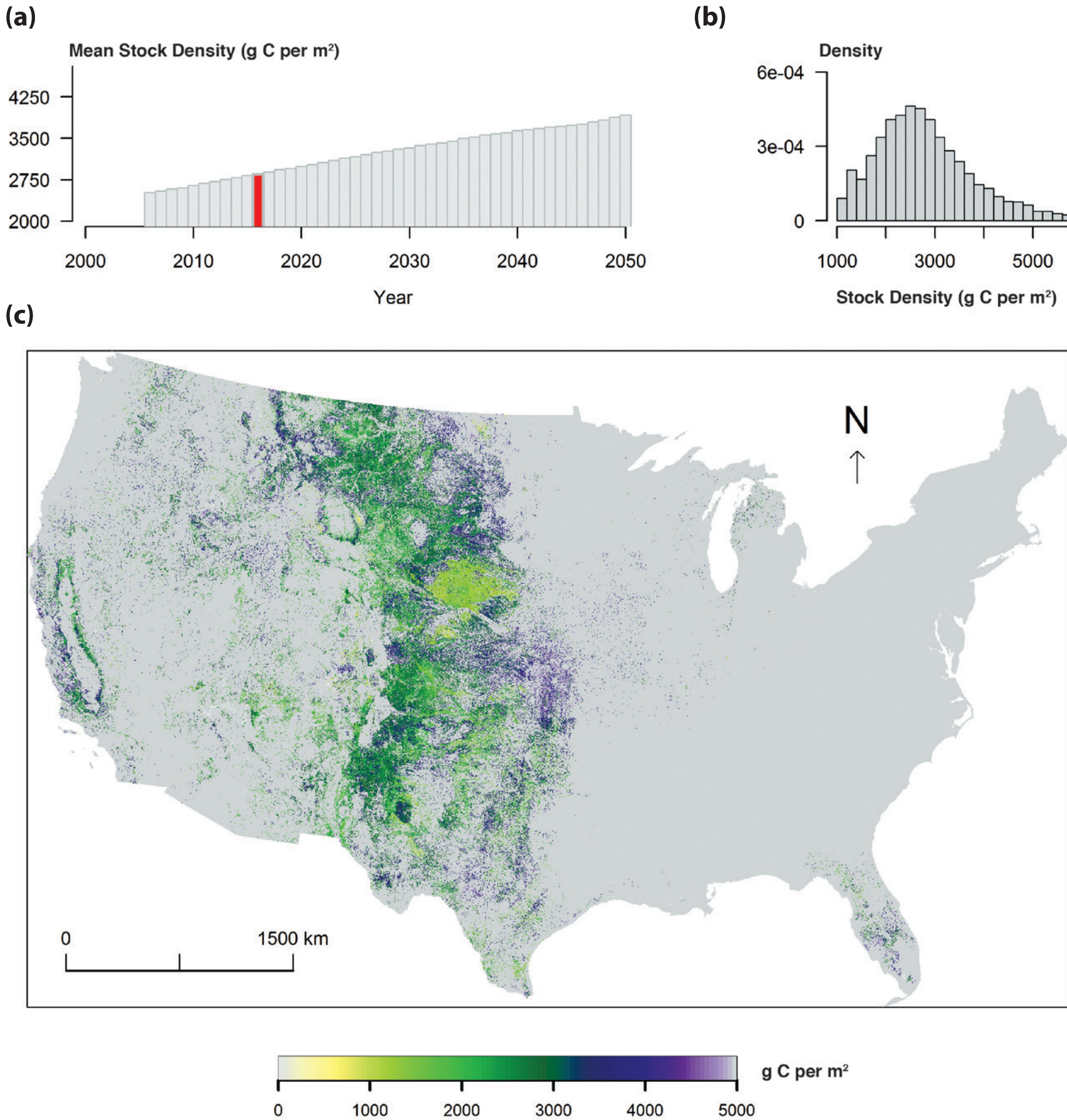
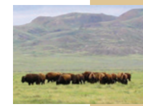


Figure 10.2. Model Simulation of Total Carbon Storage in U.S. Grasslands, 2016. (a) Spatial mean of carbon density in stocks over the 2005–2050 simulation period (red bar, 2016). **(b)** Number of pixels across the range of carbon density for 2016. **(c)** Total carbon storage in soils and vegetation for grasslands of the conterminous United States, simulated using the Erosion-Deposition-Carbon-Model (EDCM). Model simulations started in 1992 with initial soil carbon data from the Soil Survey Geographic database (SSURGO) and future climate projection from the Model for Interdisciplinary Research on Climate (MIROC; Liu et al., 2012a; Liu et al., 2014; Zhu et al., 2011). The Moderate Resolution Imaging Spectroradiometer (MODIS) net primary production products from 2001 to 2011 were used to constrain EDCM simulations, and the inverse model parameter values were used for future projections. Key: g C, grams of carbon.



summaries for 2001 to 2005 and 2006 to 2050 are shown in Table 10.2, p. 403, and Figure 10.2, p. 404. These projections represent simulation results using:

- Climate change data from the Model for Interdisciplinary Research on Climate (MIROC) general circulation model under three emissions scenarios (i.e., A1B, A2, and B1; IPCC 2000);
- Land-cover change data from the FOREcasting SCEnarios of land-use change (FORE-SCE) model (Sohl et al., 2007); and
- Three biogeochemistry models: Erosion-Deposition-Carbon Model (EDCM), CENTURY, and PBN (Liu et al., 2012b, 2014; Zhu et al., 2011).

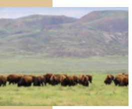
Although the USGS LandCarbon Project currently does not include new representative concentration pathway (RCP) scenarios in its biological carbon sequestration assessment, the project considers climate projections for temperature and precipitation to be quite similar between the IPCC (2000) and RCP scenarios (Knutti and Sedláček 2013).

Figure 10.2 shows the estimated spatial pattern of carbon stocks in vegetation and soil in the top 20-cm layer in 2016 and the temporal change of the mean U.S. grassland carbon stock from 2005 to 2050 under the Intergovernmental Panel on Climate Change (IPCC) scenario A1B (IPCC 2000), estimated using the EDCM model (Liu et al., 2011, 2014; Zhu et al., 2011). More information about the methodology and results from other carbon models and scenarios can be found in a series of reports (Zhu and Reed 2012, 2014; Zhu et al., 2011) and the LandCarbon project (www2.usgs.gov/climate_landuse/land_carbon). The majority of U.S. grassland is distributed in the central Great Plains ecoregion, California, and central Florida, with large spatial variability in carbon stocks. At the U.S. national scale, the mean carbon stock was projected to increase over time (see Figure 10.2, p. 404).

The spatial distribution of the current decadal mean rate of the grassland NECB is shown in Figure 10.3, p. 406. The average annual carbon uptake varied from 15 to 40 g C per m^2 per year with a decreasing trend after 2030 under scenario A1B (see Figure 10.3, p. 406). Carbon stocks were projected to continue increasing until mid-century despite declining NECB. The clear spatial pattern of the carbon fluxes from 2007 to 2016 is characterized by 1) carbon-neutral status (e.g., the Nebraska Sandhills in the central United States), 2) carbon losses mostly in north-central United States, and 3) carbon uptake mostly in the midwestern United States and California. The carbon dynamics since 2005 were simulated using the MIROC climate projections. Consequently, the simulated NECB and its spatial pattern might be different from reality, especially in the severely drought impacted areas of California in recent years.

Regional Scale: Great Plains Ecoregion as a Case Study

The Great Plains, comprising 2.17 million km^2 are dominated by grasslands, interspersed with shrublands, that account for 48% of the total area, while agricultural lands cover 42% of the total area (Zhu et al., 2011; see Figure 10.4, p. 407). Zhang et al. (2011) integrated remotely sensed vegetation greenness and weather datasets from 2000 to 2008 with NEP data from 15 eddy covariance flux tower sites to scale up and calculate a carbon budget for the Great Plains biome. The entire Great Plains was shown to have an average (± standard deviation) uptake rate of 24 ± 14 g C per m^2 per year (i.e., a range of 0.3 to 47.7 g C per m^2 per year). While the carbon uptake by the Great Plains was lower in the dry years, the entire biome remained a net carbon sink in 8 of the 9 years (Zhang et al., 2011). This study illustrated that, despite significant interannual and spatial variation, mature native grasslands have the potential to sequester significant amounts of carbon for extended periods of time (see Figure 10.4, p. 407). A recent regression tree analysis based on remote-sensing and flux tower data estimated a spatially averaged annual uptake by grasslands of 45 g C per m^2 per year in the same period (Wylie et al., 2016), confirming previous findings that grasslands are resilient carbon sinks.



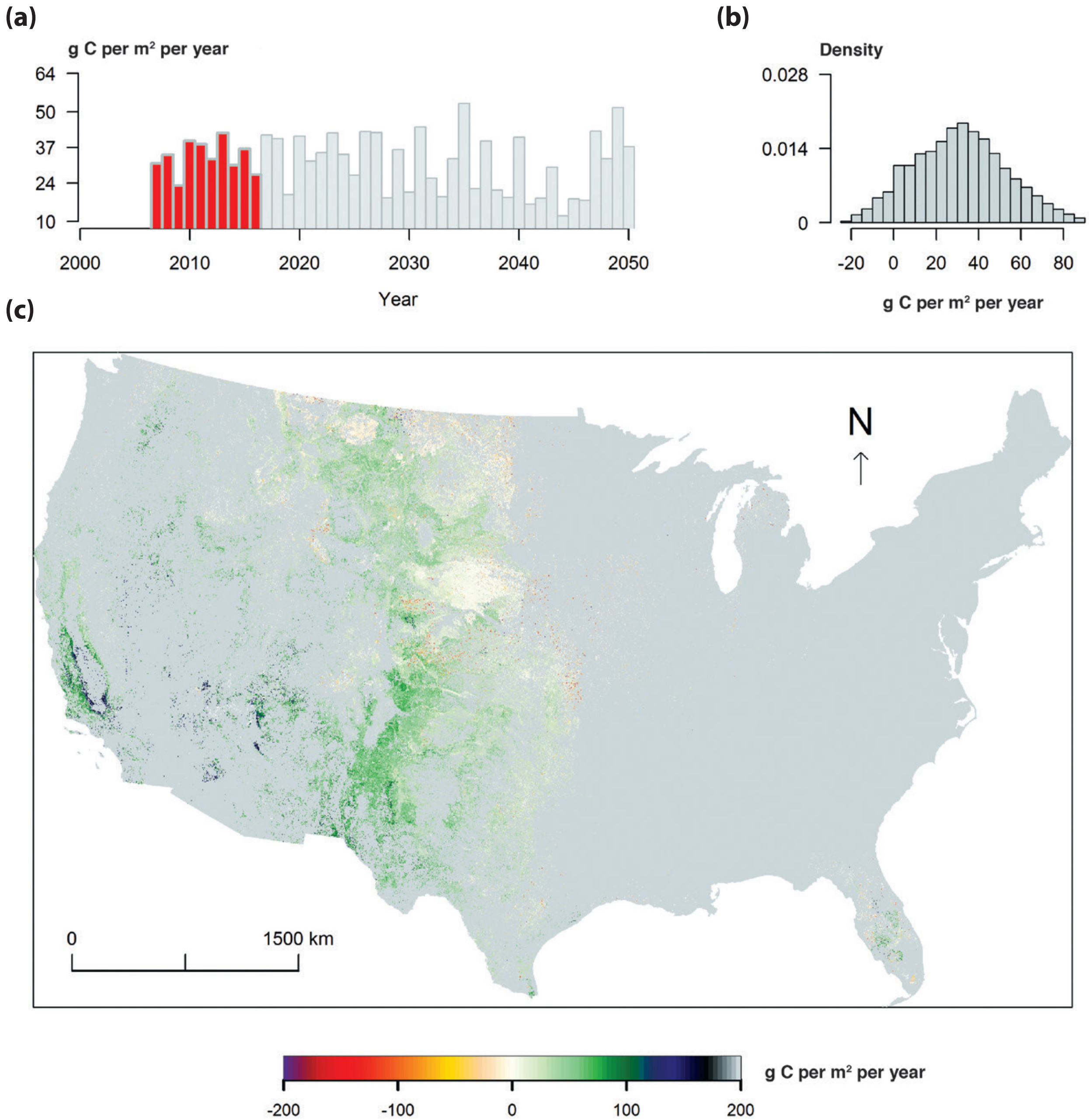
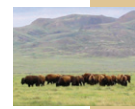


Figure 10.3. Model Simulation of Net Ecosystem Carbon Balance (NECB) for U.S. Grasslands in Response to Intergovernmental Panel on Climate Change Scenario A1B. (a) Spatial mean of NECB fluxes over the 2005–2050 simulation period (red bars, 2007–2016). Carbon increase rates are projected to decrease after 2030. **(b)** Probability of fluxes for the period 2007–2016. Positive and negative values indicate net input to and net loss from grasslands, respectively. **(c)** Spatial patterns of the decadal mean fluxes of NECB are shown from 2007 to 2016 (red portion in panel (a). Effects of climate and land-use change on NECB are combined in this simulation by the Erosion-Deposition-Carbon-Model (EDCM; Liu et al., 2014; Liu et al., 2012b; Zhu et al., 2011). Positive and negative values indicate net input to and net loss from grasslands, respectively. Key: g C, grams of carbon.



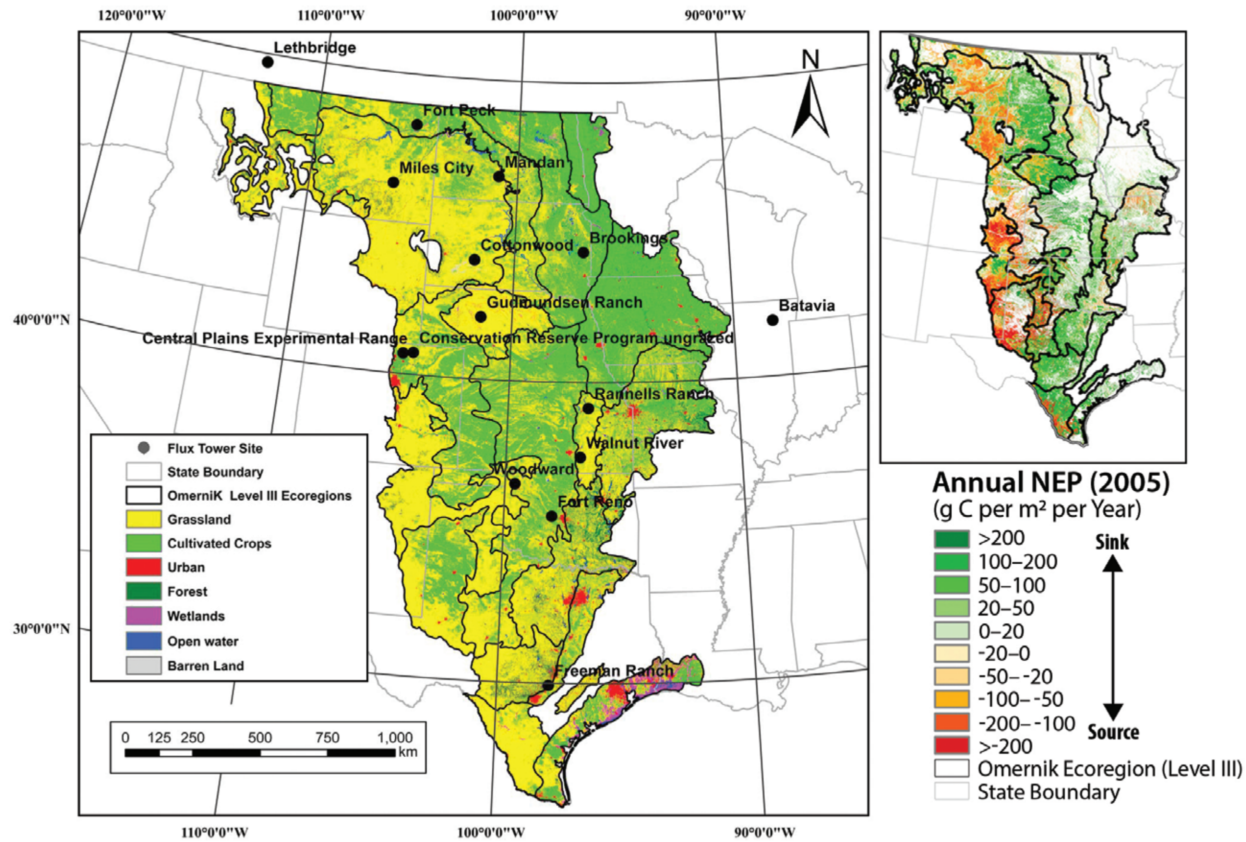
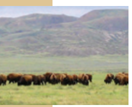


Figure 10.4. The Great Plains Ecoregion: Land Cover, Grassland Flux Towers, and Carbon Flux in 2005. The land-cover map for the Great Plains Ecoregion (Omernik 1987) was derived from the 2001 National Land Cover Database. The net ecosystem production (NEP) map was simulated based on land-cover type (Homer et al., 2004) and flux tower measurements using weather conditions for 2005. No fire disturbance or land-cover change effects were included. Key: g C, grams of carbon. [Figure source: Adapted from Zhang et al., 2011, used with permission.]

10.2.2 Processes Affecting Carbon Stocks and Fluxes in Grasslands

Climate Variability

Key Findings 2 and 3 relate to climate effects on grasslands, which will vary spatially and temporally. Grassland carbon balance is strongly sensitive to precipitation, often resulting in increased carbon losses in dry years or over drought-affected areas, particularly in the southwestern Great Plains (see Figure 10.4, this page; Biederman et al., 2016; Scott et al., 2015; Svejcar et al., 2008; Zhang et al., 2011). These frequent shifts from uptake to emissions in response to reduced precipitation indicate that grasslands are closer to the threshold for net carbon storage than are forests (Scott et al., 2015). This interannual variation in grassland NEP results from interactions between moisture and temperature controls on leaf area production, photosynthesis, and respiration (Flanagan and Adkinson 2011). If moisture is not limiting, carbon storage can increase significantly in response to warmer conditions and rising atmospheric CO_2 (see Section 10.3.3, p. 410). In part, this increase results from flexible timing of grassland plant growth and photosynthesis (Ryan et al., 2016; Zelikova et al., 2015). For example, drought decreased the growing season length and led to reductions in NPP and carbon sequestration in the Canadian Great Plains (Flanagan and Adkinson 2011).



Land-Use and Land-Cover Changes (Grazing and Species Shifts)

Key Finding 4 relates to management impacts on grassland carbon stocks and fluxes. A recent simulation suggests that Great Plains grassland area declined by 16% from 1992 to 2005 due to land-use change, including fire suppression (Bachelet et al., 2017). However, carbon stocks in remaining grasslands are considered to be stable or increasing (Zhu et al., 2011).

Grazing Effects on Grassland Carbon Cycling. Grasslands in North America evolved with native herbivores, historically grazed by livestock with varying intensities. Poor grazing management has been associated with reductions in productivity and soil carbon stocks, but improved management approaches, such as appropriate fertilization or reduced grazing intensity, can restore or even increase the original potential for carbon storage (Conant et al., 2001). Grazing intensity affects species composition and soil carbon content. For instance, heavy grazing can reduce aboveground productivity and root biomass, alter microbial community composition, and increase soil decomposition rates (Klumpp et al., 2009). However, intensive, early spring grazing may improve net carbon uptake by stimulating re-growth of plants later in the growing season, contingent on rainfall seasonality (Owensby et al., 2006; Svejcar et al., 2008). Some studies reported no effect of grazing on grassland carbon exchange (Polley et al., 2008; Risch and Frank 2006), and moderately grazed prairies can remain net carbon sinks (Frank 2004). In one recent study, moderate grazing was associated with average net carbon uptake of nearly 300 g per m^2 per year, but this was reduced to zero with heavy grazing (Morgan et al., 2016). Furthermore, low-precipitation years can reduce productivity in grazed ecosystems (Ingram et al., 2008; Polley et al., 2008), leading to net carbon losses in combination with heavy grazing (Morgan et al., 2016). In intensively managed, fertilized pastures on degraded former croplands in the mesic southeastern United States, soil carbon stocks returned to their preagricultural levels within about 6 years, because of high NPP and rapid belowground carbon cycling (Machmuller et al., 2015). In mesic Texas rangelands, adaptive management, using high stocking rates for short durations across multiple paddocks, increased soil carbon relative to continuous heavy grazing (Teague et al., 2011). These studies suggest that grassland carbon cycling is resilient to appropriately managed grazing (see Figure 10.1, p. 402). However, a global meta-analysis indicates that grazing impacts on carbon storage are contingent on many factors, including precipitation, soil texture, plant species competition, and grazing intensity; for example, grazing stimulated carbon storage in C_4 grasslands by 67% but decreased it in C_3 grasslands by 18% (McSherry and Ritchie 2013).

Species Shifts: Invasive Grasses and Woody Encroachment. The species composition, productivity, and carbon storage in grasslands are partly controlled by fire regimes, whether managed or unmanaged. Reduced fire frequency is associated with encroachment of woody plants into grassland ecosystems, while expansion of non-native, annual grasses such as cheatgrass can lead to increased fire frequency (see Figure 10.1, p. 402; Jones et al., 2015). Species shifts from perennial to annual vegetation may lead to reductions in productivity and carbon storage (Prater et al., 2006). For example, net carbon losses averaging 150 g per m^2 per year were observed for cheatgrass, mainly from increased decomposition rates (Verburg et al., 2004). Cheatgrass enhanced greenhouse gas (GHG) emissions, especially nitrous oxide (N_2O), and carbon cycling rates, compared with those for native perennial grasses (Norton et al., 2008). Further expansion of cheatgrass is expected to occur in response to rising temperatures across the western United States (Blumenthal et al., 2016).

Woody plant encroachment, with its increasing abundance of shrubs and trees, is one of the greatest threats to grasslands in North America, particularly with regard to changes in the magnitude and distribution of carbon stored in major terrestrial pools (Archer et al., 2001; Barger et al., 2011; Jackson et al., 2002; Knapp et al., 2008b). Changes in ecosystem carbon storage accompanying increases in

woody plants in grasslands represent a potentially significant but highly uncertain component of the carbon budget for North America (Houghton et al., 1999; Pacala et al., 2007), with positive, neutral, or negative effects documented (Barger et al., 2011). The most recent synthesis of studies quantifying the carbon consequences of woody plant encroachment in grasslands suggests that carbon in aboveground pools decreases in more water limited regions (i.e., mean annual precipitation < 330 mm) but increases in regions with greater precipitation (Barger et al., 2011; Knapp et al., 2008a). In the U.S. Great Plains, fire suppression with its associated woody encroachment from 1971 to 2005 is estimated to have increased total carbon stocks by an extra 5% relative to a nonfire-suppression scenario, with gains in woody biomes more than exceeding losses in grasslands (Bachelet et al., 2017). Changes in soil carbon from woody encroachment were not strongly related to aboveground carbon. However, loss of soil carbon is most likely to occur in humid grasslands, with increases in soil carbon apparent in arid regions (Barger et al., 2011; Jackson et al., 2002). Combining major aboveground and belowground pools, Barger et al. (2011) concluded woody plant encroachment generally would result in a net increase in ecosystem carbon stocks. Although some shrub-dominated ecosystems are more likely to lose carbon during drought periods than nearby grass-dominated systems (Scott et al., 2015), other areas indicate shrubs can maintain net carbon uptake despite drought (Petrie et al., 2015).

Woody plants are still increasing in many grasslands as a result of reduced fire frequency, rising CO_2, and increased precipitation intensity (Kulmatiski and Beard 2013). Because changes in carbon pools occur at very different rates above and below ground, ecosystem carbon changes driven by woody plant encroachment are likely to remain dynamic in the future. Overall, shifts in plant species composition and ecosystem structure represent a significant source of uncertainty in predicting future carbon cycling in grasslands.

10.3 Indicators, Trends, and Feedbacks

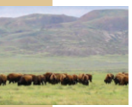
10.3.1 Future Projections of Carbon Stocks and Fluxes in Conterminous U.S. Grasslands

In estimating carbon stock and fluxes, several different models were used (see Key Finding 1, p. 400) to assess their projections, The LandCarbon project simulated future carbon stocks (see Figure 10.2, p. 404) and fluxes (see Figure 10.3, p. 406) using projections from MIROC A1B, A2, and B1 climate scenarios; FORE-SCE model; and EDCM (Liu et al., 2012b, 2014). Thus, these simulations combine the effects of land-use change and climate on carbon sequestration by grasslands in the conterminous United States (see Table 10.2, p. 403). While these model predictions are useful as general guidelines, additional empirical and simulation experiments are needed to disaggregate the effects of land-cover change from those of climate change and to examine regional differences in carbon cycling.

10.3.2 Impacts of Land-Use and Land-Cover Change on Future Carbon Cycling

Zhu et al. (2011) demonstrate that land-use and land-cover conversions were major drivers of the predicted changes in carbon storage in Great Plains grasslands. Future land-use change in the region (data provided by the *Intergovernmental Panel on Climate Change's Special Report on Emission Scenarios*; IPCC 2000) is driven by the demand for agricultural commodities, including biofuels, resulting in a 1.4% to 9.2% expansion of agricultural land by 2050, mostly at the expense of grasslands (–2.2% to –9.3%). Areas where woody vegetation expands into grassland because of fire suppression are re-classified as forest. This change tends to result in higher carbon stocks and uptake rates but also can be subject to catastrophic carbon losses in hot and dry fire years following wet years' boosting of fuel loads (Bachelet et al., 2017).

In the Great Plains, carbon stocks for the years 2001 to 2005 are assessed as 7,500 Tg C with 45.8% in agricultural lands, 34.9% in grasslands and



shrublands, 15.5% in the few existing forested areas, and almost 3% in wetlands. By 2050, models estimate those percentages will change to reflect a small increase in agricultural land carbon stocks (47%), a large decrease in grassland carbon stocks (29%), an increase in forestland carbon stocks (20.4%) due to woody encroachment and forest growth, and no change in carbon stocks of wetlands or other lands. Conversion of grasslands to agriculture may lead to a cumulative reduction in stored carbon of 26 to 157 Tg from 2001 to 2050, an amount which could contribute up to 4% loss of mean total carbon sequestration potential (Zhu et al., 2011). Shrub encroachment and afforestation cannot mitigate carbon losses to agricultural expansion. Fires are also a source of carbon loss. Areas burned and carbon emissions from fires vary both spatially and temporally due to climatic, biological, and physical factors. However, fires in grasslands were not projected to change significantly under future climate conditions when models did not include the role of annual invasives or fire suppression. Average fire emissions from grasslands range from 0.18 to 24.72 Tg CO_2 equivalent[1] (CO_2e) per year (Zhu et al., 2011).

10.3.3 Climate Change Impacts on Grassland Productivity

Numerous environmental factors interact to affect grassland production, including warming, rising CO_2, hydrology, and nutrient availability. Grassland productivity is very sensitive to variations in climate, especially precipitation and including both the mean and extremes such as droughts and floods (Huxman et al., 2004; Knapp et al., 2001, 2008b, 2015). Their sensitivity indicates a strong potential for climate change to alter carbon cycling in grasslands (see Key Finding 2, p. 400; Figure 10.5, p. 411). Productivity is predicted to decline in the southwestern United States and northern Mexico as a result of reduced precipitation and to increase in the northern Great Plains as a result of temperature and precipitation increases that allow an increase in growing season length (Hufkens et al., 2016; Polley et al., 2013; Reeves et al., 2014). However, significant projected increases in productivity did not arise until after 2030 because of scenarios projecting CO_2 fertilization and rising temperatures (Reeves et al., 2014).

North American grassland growth in this century was simulated based on hydrology and repeat-photography observations of vegetation greenness (Hufkens et al., 2016). Despite a projected increase in climate aridity by 2100, increases in fractional plant cover were predicted over almost 90% of the study area, with greater increases in cover and net carbon sequestration in the more northerly areas. The primary mechanism contributing to the projected increase in grassland growth was a shift to earlier leaf emergence in the spring and delayed leaf senescence in the autumn, both of which compensated for drought-induced reduction in plant productivity during the summer (Hufkens et al., 2016).

Predictions from the vegetation-hydrology model are supported by a climate manipulation experiment in Wyoming mixed-grass prairie, where the growing season started earlier in spring because of the warming treatment and ended later in autumn because of increased soil moisture made available by the elevated CO_2 treatment (Reyes-Fox et al., 2014). The lengthening of the growing season was dependent on a mix of C_3 and C_4 species adapted to different climate conditions. In the same experiment, greenness was enhanced (i.e., indicating increased aboveground biomass and cover) with warming and elevated CO_2, but the effects of seasonal and interannual rainfall variability were much stronger (Zelikova et al., 2015). High-precipitation years had two to three times greater vegetation greenness than dry years. Warming in combination with elevated CO_2 increased total plant biomass by an average of 25%, especially below ground (Mueller et al., 2016). Warming and elevated CO_2 also interacted to affect soil moisture and nitrogen availability (Mueller et al., 2016). While elevated CO_2 conditions increased soil moisture (Morgan et al., 2011), warming decreased soil moisture, and soil nitrate tended to follow trends opposite to those for elevated CO_2 (Mueller et al.,

[1] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for details.

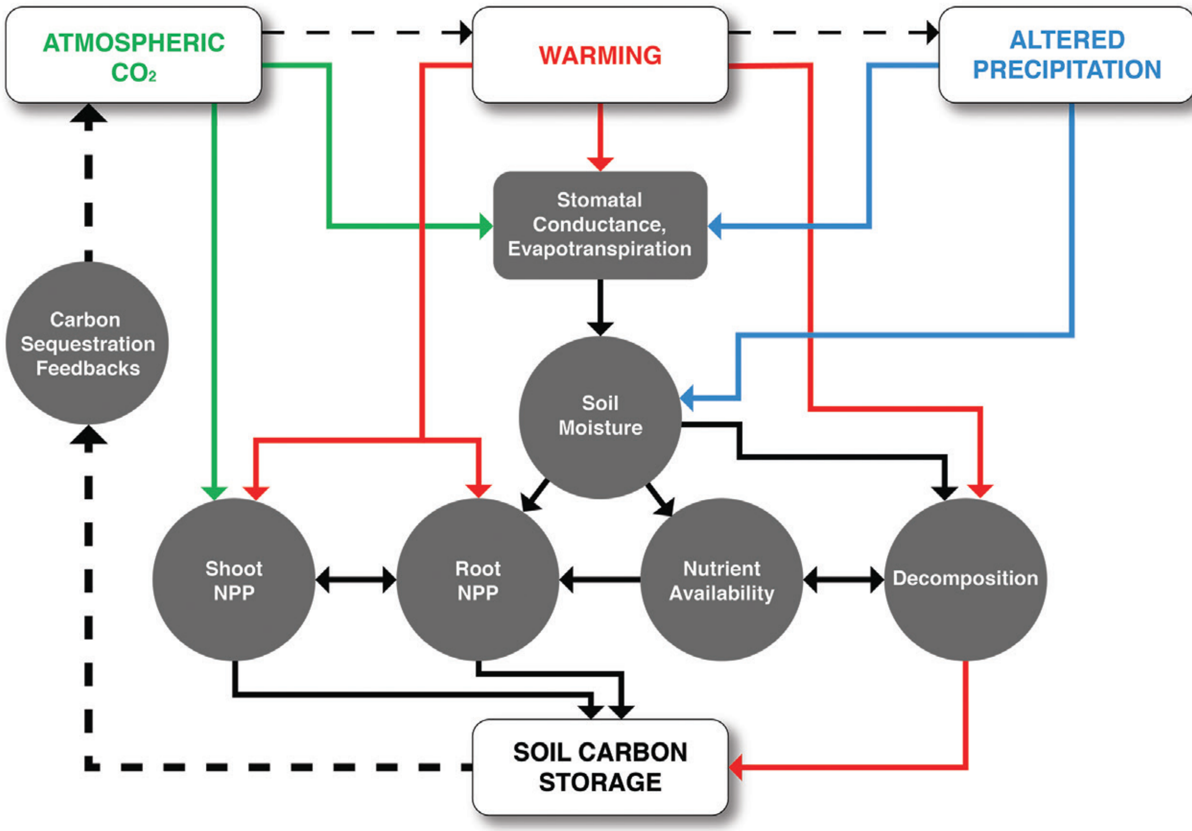
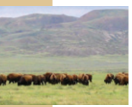


Figure 10.5. Interacting Effects of Rising Atmospheric Carbon Dioxide (CO_2), Warming, and Altered Precipitation on Grasslands. Climate variations can impact grassland plant productivity and soil organic matter (SOM) storage, which in turn are mediated by soil moisture and nutrient availability. Root and shoot net primary production (NPP) are correlated, and both are dependent on soil moisture and nutrient availability. Plant nutrient uptake can decrease soil nutrients, which may be made available during SOM decomposition. [Figure conception derived from numerous studies, including Hufkens et al., 2016; Morgan et al., 2011; Mueller et al., 2016; Reich and Hobbie 2013; Reyes-Fox et al., 2014; and Zelikova et al., 2015.]

2016). A warming experiment in desert grasslands suggested warming could reduce C_3 and C_4 grass carbon fixation rates and aboveground biomass, with no significant effects on shrub photosynthesis or growth (Wertin et al., 2015, 2017). Figure 10.5, this page, illustrates carbon cycle interactions and feedbacks associated with multiple climate change factors. Furthermore, changing seasonality of precipitation events, as well as more extreme weather conditions, are expected to affect carbon cycling increasingly more in the future (Knapp et al., 2008b).

Nutrient limitation may reduce the potential for CO_2 fertilization in grasslands, especially over decadal timescales (see Figure 10.5, this page). For example, a long-term experiment in a nutrient-poor grassland in Minnesota revealed that elevated CO_2 effects on NPP were dependent on soil nitrogen availability and experiment duration. During the first 3 years of the experiment, elevated CO_2 stimulated aboveground biomass by 11% and was not contingent on nitrogen availability, but over the longer term (4 to 13 years), the biomass response to elevated CO_2 increased by up to 20% with added nitrogen fertilizer (Reich and Hobbie 2013). However, in the coming decades, elevated temperature may enhance nitrogen availability, as shown by Mueller et al. (2016). Moreover, increasing nitrogen



deposition will stimulate NPP, up to a threshold, and GHG emissions also may follow a similar nonlinear response to nutrient loading (Gomez-Casanovas et al., 2016). Interacting effects of multiple global change factors still represent a large source of uncertainty in predicting carbon cycle responses (Norby and Luo 2004).

10.3.4. Trends and Climate Feedbacks from Soil Carbon Cycling

The effect of climate change on the stability of carbon in SOM pools is one of the largest sources of uncertainty in projections of climate-carbon interactions (Heimann and Reichstein 2008) because these pools are large and vulnerable to climate change (Davidson and Janssens 2006; see Key Finding 3, p. 400). In grasslands, decomposition of roots is thought to drive SOM accumulation (Jackson et al., 1996; Jobbagy and Jackson 2000), so processes affecting belowground productivity are likely to affect soil carbon storage (see Figure 10.5, p. 411). The importance of impacts from aboveground inputs compared to those from direct inputs via root production depends on climate, soil type, and plant species (Sanderman and Amundson 2008). Therefore, grassland species composition and productivity, both above and below ground, and their responses to climatic and land-use changes are key determinants of soil carbon storage. SOM decomposition rates vary with temperature and moisture and can be affected by plant-microbe interactions (van Groenigen et al., 2014) via nutrient uptake processes (Nie and Pendall 2016).

Soil Carbon Responses to Altered Precipitation. Precipitation is the most important climate driver of productivity in grasslands (Knapp and Smith 2001) and is likely to influence carbon storage in soils over longer timescales, via mechanisms related to both plant inputs and decomposition losses (see Figure 10.5, p. 411). A meta-analysis indicated that soil carbon content increased in response to both reductions and additions of moisture in grasslands (Zhou et al., 2016). Experimentally increased precipitation likely enhanced soil carbon pools via the stimulation of biomass inputs, whereas reduced precipitation may have enhanced the soil carbon pools by reducing SOM decomposition rates as well as by increasing allocation to root biomass production (Zhou et al., 2016).

Soil Carbon Responses to Warming. Earth System Models (ESMs) assume that warming will stimulate SOM decomposition at an exponential rate, leading to potentially strong positive feedbacks to climate change (Figure 10.5; Davidson and Janssens 2006). Experimental evidence of this assumption has been accumulating from numerous individual studies worldwide (Luo 2007). A recent synthesis of warming-experiment results confirms that SOM is vulnerable to warming and indicates that the magnitude of carbon loss depends on initial carbon stocks (Crowther et al., 2016). This study also showed that deserts and arid grasslands, with lower soil carbon pools, are less vulnerable to warming than colder ecosystems. A reduction in decomposition rates with warming-induced soil desiccation could potentially explain these results (Pendall et al., 2013).

Using results from field experiments to inform model parameters is a powerful way to reduce uncertainties, constrain the models, and enhance modeling tools to extrapolate results more broadly. Data from a 9-year warming experiment in tallgrass prairie were assimilated into a biogeochemistry model to demonstrate that soil carbon pools would decrease over the coming century (Shi et al., 2015). This study confirms that carbon in productive grasslands like the tallgrass prairie in Oklahoma can be vulnerable to warming, in part because of the resulting increased decomposition of a large, partially protected soil carbon pool. Key uncertainties were related to the mismatch between the long-term residence time of the large, recalcitrant soil carbon pool and the duration of the experiment (Shi et al., 2015).

Soil Carbon Responses to Rising CO_2 and Interactions with Multiple Drivers. While rising atmospheric CO_2 concentrations can stimulate grassland productivity above and below ground, especially in combination with warming (Mueller et al., 2016), increased productivity has not necessarily translated

into increased soil carbon storage (Luo et al., 2006). A meta-analysis revealed that carbon inputs to grasslands increased by 20% with experimentally increased CO_2, but this increase was accompanied by a 16.5% increase in the decomposition rate constant (van Groenigen et al., 2014). The "priming effect" that stimulates SOM decomposition may be caused by the increased microbial activity caused by increased belowground carbon inputs (Carney et al., 2007) and soil moisture (Pendall et al., 2003), and this effect may be "widespread and persistent" (van Groenigen et al., 2014). A simulation model calibrated to realistic field conditions in semiarid Wyoming grassland predicted that soil carbon would decrease with elevated CO_2 and increase with warming, because of indirect effects mediated by soil moisture (Parton et al., 2007). However, the importance of interactive effects of multiple climate changes in predictions of long-term soil carbon storage still needs to be confirmed with field results.

Few field experiments have been conducted that combine two or more climate drivers over a long enough duration to evaluate soil carbon responses (Luo et al., 2011), making realistic predictions of soil carbon sequestration challenging. A recent meta-analysis failed to uncover significant changes in soil carbon with the combined effects of elevated CO_2 and temperature, although belowground (i.e., root) production was significantly stimulated (Dieleman et al., 2012). While synthesis studies and meta-analyses are useful for discovering general patterns, they cannot distinguish mechanisms underlying these patterns. Major uncertainties in soil carbon storage and ecosystem carbon cycling remain because there are too few long-term, multifactor climate manipulation experiments to constrain mechanisms, feedbacks, and interactive effects among global change drivers.

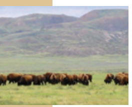
10.4 Societal Drivers, Impacts, and Carbon Management

Because grassland vegetation is predominantly herbaceous (i.e., nonwoody), biomass carbon stocks in grassland systems are a small, transient carbon pool with soil constituting the dominant carbon stock. The main processes governing the carbon balance of grassland soils are the same as for other ecosystems—the photosynthetic uptake and assimilation of CO_2 into organic compounds and the release of gaseous carbon, primarily CO_2 but also methane (CH_4), through respiration and fire (see Key Finding 4, p. 400). In grasslands, carbon assimilation is directed toward production of forage by manipulating species composition and sometimes growing conditions (e.g., soil fertility and irrigation).

10.4.1 Grazing Management

For most grasslands in North America, grazing management is the primary feasible management practice that can be manipulated to alter soil carbon stocks. The capacity to increase grassland system carbon stocks is a function of 1) carbon stock changes that might be realized with a shift from suboptimal to best management practices and 2) the areal extent of grasslands that are not optimally managed (Conant and Paustian 2004). Estimates of the potential to sequester carbon in North American grasslands by improving grazing management practices seem likely to be on the order of tens of teragrams of carbon per year (Follett et al., 2001). Uncertainty across these and similar estimates stems from variation in soil carbon responses to management practices, which vary substantially from place to place. Some uncertainty also arises from limited information about past management and the extent to which those historical practices have depleted soil carbon stocks. Additionally, plot-level research indicates that a wide variety of practices could drive increases in soil carbon stocks (Chambers et al., 2016; Conant et al., 2001; Henderson et al., 2015). What is not clear is whether practices used in field experiments can be replicated reasonably under real-world conditions or the extent to which experiments are indicative of potentially observed real-world carbon stock rate changes (Conant et al., 2017).

Removal of some (30% to 50%) aboveground biomass through grazing can reduce the amount of carbon returned to the soil, potentially leading to reduced soil carbon stocks (Conant et al., 2017).



Similarly, shifts in species composition in response to grazing could lead to reductions in carbon inputs and soil carbon stocks. Some of the carbon lost from grassland soils can be recovered with changes in management practices that increase carbon inputs, stabilize carbon within the system, or reduce carbon losses (Conant et al., 2017; Eagle and Olander 2012). Adaptive and intensive grazing practices can increase soil carbon stocks (Machmuller et al., 2015; Teague et al., 2011). However, the management practices that promote soil carbon sequestration would need to be maintained over decades to avoid subsequent losses of sequestered carbon.

10.4.2 Fire Suppression and Woody Encroachment

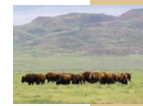
Grazing management, fire suppression, and climate interactively control grassland species composition and productivity, and these responses vary regionally. Woody plant cover is increasing in many grasslands because of management activities such as fire suppression and anthropogenic GHG emissions that increase atmospheric CO_2 concentrations (Kulmatiski and Beard 2013). The most recent syntheses suggest that carbon in aboveground pools decreases in regions with more-limited water (mean annual precipitation < 330 mm) but increases in regions with greater precipitation (Barger et al., 2011; Knapp et al., 2008b). For example, fire suppression in Kansas allowed the expansion of *Juniperus virginia* that was associated with rapid increases in carbon stocks in vegetation and soils (McKinley and Blair 2008). In the more arid Chihuahuan Desert, shrub encroachment related to historical over-grazing led to higher net carbon uptake rates (Petrie et al., 2015) but may lead to additional loss of grass vegetation (Thomey et al., 2014). Soil carbon pools may increase with woody encroachment, depending on other disturbance factors, especially fire (Barger et al., 2011). If management policies continue to allow woody plants to expand into native grasslands, the central United States may become a significant regional carbon sink (McKinley and Blair 2008), given sufficient precipitation.

Regional responses to management and climate change are partly related to distinct evolutionary pressures. The combination of grazing and aridity in the Great Plains grasslands may have favored traits that impart resistance to both those disturbances (Milchunas et al., 1988; Moran et al., 2014; Quiroga et al., 2010). In contrast, desert grasslands evolved the ability to rapidly respond to and effectively use highly variable precipitation (McClaran 1997), though often requiring years to recover from disturbance (Peters et al. 2012) and thus allowing rapid expansion of woody species (McClaran et al., 2010). If the frequency of burning increases in mesic tallgrass prairie, decreased nitrogen may become a limiting factor, eventually diminishing aboveground production (Soong and Cotrufo 2015). Thus, fire regime management can influence carbon storage via its effects on above- and belowground production, as well as inputs of recalcitrant, pyrogenic organic matter to soil.

10.4.3 Land Conversion

Agricultural policies can have a large influence on land-use change. For example, in the U.S. Great Plains during 1973 to 2000, grassland and shrubland area expanded by 2.2% while agricultural area decreased by 1.8%, in part related to farm policy programs such as the Conservation Reserve Program (CRP; landcovertrends.usgs.gov/gp/eco43Report.html). However, the area held in CRP peaked in 2007 at 37 million acres and has since declined (Ahlering et al., 2016). In the coming three decades, agricultural expansion is expected to continue to reduce the extent of grasslands by 2% to 9% by 2050 (see Section 10.3.2, p. 409; Zhu et al., 2011), depending on annual crop prices (Stubbs 2014).

Grasslands generally take up and store more carbon than croplands; for example, in the Great Plains, the average uptake rates were about 45 g C per m^2 per year for grasslands and 31 g C per m^2 per year for croplands from 2000 to 2008 (Wylie et al., 2016). Soil carbon losses occur when native grasslands are initially tilled, with the amount determined by the tillage method and the soil's initial carbon content. In a modeling study, this "carbon debt" was repaid



after 2 to 25 years of no-till corn ethanol production, but that process was 50% longer in a full-tillage production scenario (Kim et al., 2009). Moreover, GHG emissions from croplands tend to be higher than those from grasslands, especially when CH_4 and N_2O are considered. Protection of grasslands from conversion to croplands in the northern mixed-grass prairie pothole region of the Dakotas would reduce emissions significantly, but carbon offsets alone cannot compete with high market prices for corn (Ahlering et al., 2016). For more details on the effects of agricultural management on carbon cycling, see Ch. 5: Agriculture, p. 229.

10.5 Synthesis, Knowledge Gaps, and Outlook

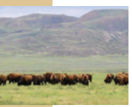
10.5.1 Synthesis

Grasslands are globally important carbon sinks that are resilient to climate change and managed grazing because the mixture of native species that occur are adapted to variable climatic conditions and grazing pressure. In drier regions, such as the southwestern United States and Mexico, grasslands may lose carbon in response to droughts or overgrazing. Mesic grasslands in Florida have stored vast amounts of soil carbon, which may be vulnerable to losses from fire and flooding, and CH_4 emissions from these and other poorly drained grasslands can be significant. Changes in the geographic extent of grasslands caused by land-use change, including cropping and grazing management, will affect grassland carbon cycling. The net uptake rate of carbon is higher in grasslands than in agricultural lands, but management that takes carbon storage into consideration may mitigate potential carbon losses. Invasive species also are likely to alter grassland carbon cycling: woody species such as juniper or mesquite may increase net carbon uptake while herbaceous invasive species, such as cheatgrass, may diminish net carbon uptake.

10.5.2 Knowledge Gaps

Grassland productivity and carbon cycling are linked very closely to variations in precipitation and soil moisture availability in space and time. Changes in climate that lead to altered moisture availability are likely to affect the ability of grasslands to store carbon. Therefore, one of the main sources of uncertainty in predicting grassland carbon cycling is related to predictions of future precipitation, in terms of means, extremes, and seasonal distribution. The forecasted intensification of the global hydrological cycle will manifest in many ways, including increased interannual precipitation variability, more frequent extreme precipitation years (wet and dry), and alterations in annual precipitation amount (IPCC 2013). Recent climatological trends have supported these predictions (Fischer and Knutti 2014; Min et al., 2011). In grasslands, carbon uptake processes have been shown to be quite responsive to precipitation amount and event size and timing (Cherwin and Knapp 2012; Goldstein and Suding 2014; Heisler-White et al., 2008, 2009; Knapp et al., 2008b; Kulmatiski and Beard 2013; Thomey et al., 2011), but both positive and negative effects have been documented. Resolving the effects on carbon cycling from altered precipitation regimes—including seasonality—in future grasslands will reduce uncertainty in responses (Knapp et al., 2008b). Moreover, also unknown are future effects on carbon cycling from interactions between climate change and species composition. Additional simulations with dynamic vegetation models, including management parameters such as fire suppression, will help reduce these uncertainties (Bachelet et al., 2017).

Model intercomparison projects that address large differences in future projections of carbon cycling in grasslands and other ecosystem types also will reduce uncertainties (Medlyn et al., 2015). Methodological differences in estimating regional- to continental-scale carbon stocks and fluxes have resulted in large apparent uncertainties in budgets. For inventory methods, these uncertainties appear to stem from extrapolating carbon stocks and fluxes from point measurements to regional scales based on land-use classifications. For land-surface models, uncertainties can result from different assumptions, drivers, and processes. For atmospheric inverse models, the attribution of specified land areas may not align well with other approaches. For all these

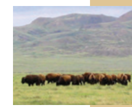


methods, inconsistencies in the depth of soil carbon can lead to large differences in stocks and process rates. Reconciling these divergent results likely will lead to improved understanding of processes and narrow the range of uncertainty in carbon forecasts.

Projections of soil carbon trends in response to future climate and land-use changes remain highly uncertain, particularly in warm, dry areas of Mexico and the U.S. Southwest and at high northern latitudes where data to inform modeling are limited. One uncertainty is related to the depth of soil carbon storage, with most models considering only the top 20 cm. However, validation and calibration datasets are not readily available, so models are rarely updated (e.g., Liu et al., 2003), and there is disagreement about which drivers of soil carbon dynamics should be included in models (Wieder et al., 2015). A recent study that simulated results from several multifactor climate change experiments indicated that productivity and decomposition responded more to increased precipitation and elevated CO_2 in drier sites, including grasslands, than they did in wetter sites (Luo et al., 2008). The four tested ecosystem models all demonstrated significant interactive effects of warming, elevated CO_2, and altered precipitation, although results for different sites varied because model formulations differed (Luo et al., 2008). These disparate findings demonstrate that rigorously evaluating model assumptions against experimental results will improve ESM projections (Medlyn et al., 2015).

10.5.3 Outlook

Grasslands, the most extensive land-use type in the continental United States when combined with rangelands, shrublands, and pastures (Reeves and Mitchell 2012), are expected to maintain net carbon uptake at least until the middle of this century. The most significant threats to this carbon uptake potential likely will be related to land management and land use, along with changes in the precipitation regime associated with ongoing climate change.



SUPPORTING EVIDENCE

KEY FINDING 1

Total grassland carbon stocks in the conterminous United States, estimated to be about 7.4 petagrams of carbon (Pg C) in 2005, are projected to increase to about 8.2 Pg C by 2050. Although U.S. grasslands are expected to remain carbon sinks over this period, the uptake rate is projected to decline by about half. In the U.S. Great Plains, land-use and land-cover changes are expected to cause much of the change in carbon cycling as grasslands are converted to agricultural lands or to woody biomes (*medium confidence*).

Description of evidence base

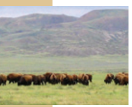
Total carbon stocks are from Table 10.2, p. 403, based on LandCarbon project estimates (landcarbon.org/categories). Various efforts confirm that the U.S. and North American grasslands in recent years have been a weak carbon sink (i.e., mostly within the range of 10 to 40 g per m^2 per year; Hayes et al., 2012; Liu et al., 2012b; Raczka et al., 2013; Wylie et al., 2016; Xiao et al., 2014; Zhang et al., 2011). Recent results generated from the assessment of carbon sequestration potentials in the United States conducted by the U.S. Geological Survey (Zhu and Reed 2012, 2014; Zhu et al., 2011) provided more integrated grassland carbon assessment. Land-use change scenarios and spatial dynamics were developed empirically by ecoregions across the United States under the Intergovernmental Panel on Climate Change (IPCC) scenarios A1B, A2, and B1 (Sleeter et al., 2012; Sohl et al., 2007), which are considered to be similar to representative concentration pathway (RCP) scenarios (Knutti and Sedláček 2013). Carbon dynamics in grassland ecosystems were simulated with the General Ensemble Biogeochemical Modeling System (GEMS) using three climate projections: the Second Generation Coupled Global Climate Model (CGCM2), Australia's national Commonwealth Science and Industry Research Organization (CSIRO), and Model for Interdisciplinary Research on Climate (MIROC) for each of the three IPCC scenarios (Liu et al., 2012b, 2014). The data included in this report include simulations from two process-based models: CENTURY (Parton et al., 1987) and the Erosion-Deposition–Carbon-Model (EDCM; Liu et al., 2003), and both were encapsulated in GEMS. The findings are supported by a recent synthesis of eddy covariance data with remote sensing, which shows that grasslands take up somewhat more carbon than crops in the Great Plains, although both were weak carbon sinks from 2000 to 2008 (Wylie et al., 2016).

Major uncertainties

There are significant differences in evaluation of grassland carbon stocks and fluxes (Hayes et al., 2012; Raczka et al., 2013; Zhu and Reed 2014). The primary source of model difference comprises modeling method (i.e., inventory, flux towers, inversion, and process-based modeling) and land-cover characterization and spatial resolution. For example, the LandCarbon study (Zhu and Reed 2012, 2014; Zhu et al., 2011) combined grass and shrub into grassland and considered fire disturbance, while Zhang et al. (2011) used data from 15 flux towers at natural grassland and pastures or hay sites but without considering fires.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

The magnitudes of the estimates of carbon stocks and fluxes vary depending on the method used, indicating a medium to low level of confidence in the results.



Summary sentence or paragraph that integrates the above information

Grasslands appear very likely to be weak carbon sinks and will remain so for at least the coming three decades, but reconciling different methods will reduce uncertainties in the quantities.

KEY FINDING 2

Increasing temperatures and rising atmospheric carbon dioxide (CO_2) concentrations interact to increase productivity in northern North American grasslands, but this productivity response will be mediated by variable precipitation, soil moisture, and nutrient availability (*high confidence, very likely*).

Description of evidence base

Experimental manipulations in the field provide evidence of climate change effects on grassland productivity by up to 33%, but this is contingent on nutrient and moisture availability (e.g., Morgan et al., 2011; Mueller et al., 2016; Reich and Hobbie 2013). Spatially distributed observations of vegetation phenology (i.e., greenness) and carbon fluxes combined with empirical modeling provide evidence of regional differences in grassland responses to future climate change (Hufkens et al., 2016). Simulation models are in general agreement with empirical evidence that carbon stocks will increase in grasslands in the coming three to four decades (Zhu et al., 2011). In grasslands, carbon uptake is responsive to precipitation amount and event size and timing, with both positive and negative effects documented, but droughts are associated with carbon losses across all grasslands (Cherwin and Knapp 2012; Goldstein and Suding 2014; Heisler-White et al., 2008, 2009; Knapp et al., 2008b; Kulmatiski and Beard 2013; Thomey et al., 2011).

Major uncertainties

The largest source of uncertainty is related to future precipitation regimes in the grassland biomes of North America, with both increases and decreases in precipitation predicted (IPCC 2013). The degree to which altered precipitation regimes will affect carbon cycling in future grasslands is uncertain (Knapp et al., 2008b). The relative response of grassland productivity to moisture availability is contingent upon prior conditions, which vary temporally and spatially (Heisler-White et al., 2009). Empirical models represent grassland phenology and productivity well, but they lack explicit physiological processes, leading to uncertainties in mechanisms underlying ecosystem responses to climate change (Hufkens et al., 2016).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Confidence is high that grassland production will increase with precipitation as atmospheric CO_2 and temperature increase in the coming three to four decades, based on empirical evidence from field experiments.

Estimated likelihood of impact or consequence, including short description of basis of estimate

If grassland productivity decreases in response to climate change, such as reduced precipitation, forage production for livestock is very likely to be at risk. This has been demonstrated by numerous experiments and models as explained above in the description of evidence base.

Summary sentence or paragraph that integrates the above information

Grassland productivity is highly likely to respond positively to increased precipitation and temperature, especially in the Northern Great Plains. Neutral or negative responses of productivity to warming in the Southern Great Plains, the southwestern United States, and Mexico may be offset by positive responses to elevated CO_2.

KEY FINDING 3

Soil carbon in grasslands is likely to be moderately responsive to changes in climate over the next several decades. Field experiments in grasslands suggest that altered precipitation can increase soil carbon, while warming and elevated CO_2 may have only minimal effects despite altered productivity (*medium confidence, likely*).

Description of evidence base

Meta-analysis of numerous field experiments showed that soil carbon stocks increase when precipitation is increased or decreased in grasslands (Zhou et al., 2016). Meta-analysis also showed that elevated CO_2 increased soil carbon decomposition rate, limiting carbon storage potential (van Groenigen et al., 2014). Field experiments indicate that soil carbon stocks decrease with warming, especially in regions where stocks are high to begin with (Crowther et al., 2016), although warming-induced soil carbon losses from grasslands may be insignificant (Lu et al., 2013). These results are confirmed in some simulation experiments (e.g., Parton et al., 2007; Shi et al., 2015).

Major uncertainties

Major uncertainties in soil carbon storage come from insufficient understanding of physical and biological mechanisms that determine the stability of soil carbon. Physical mechanisms underlying carbon stability in soil, such as protection within aggregates and their sensitivity to climate change, are still poorly described (Heimann and Reichstein 2008). In particular, regulation of soil organic matter decomposition by microbe-plant interactions is poorly understood and not well represented in models (Wieder et al., 2015). Improving mechanistic understanding of soil carbon dynamics, and incorporating key mechanisms into models, will reduce uncertainties in future carbon cycle predictions (Todd-Brown et al., 2013).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

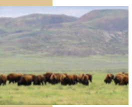
Mechanistic understanding of soil carbon stability in the face of climate change is still limited, leading to only medium confidence levels regarding the response of soil carbon to climate changes.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Soils in grasslands are not likely to respond strongly to climate change; small carbon losses or gains could occur in the future with warming or elevated CO_2. Larger carbon gains are likely to occur with increased precipitation.

Summary sentence or paragraph that integrates the above information

Mechanisms regulating soil carbon storage in response to climate change can be incorporated into models to improve confidence in model predictions of future carbon cycling.



KEY FINDING 4

Carbon stocks and net carbon uptake in grasslands can be maintained with appropriate land management including moderate levels of grazing. Fire suppression can lead to encroachment of woody vegetation and increasing carbon storage in mesic regions, at the expense of grassland vegetation (*high confidence, likely*).

Description of evidence base

Studies of carbon fluxes using eddy covariance indicate that moderate grazing allows grasslands to continue to be net carbon sinks, but heavy grazing diminishes their capacity to take up carbon (Frank 2004; Morgan et al., 2016; Polley et al., 2008; Risch and Frank 2006). Soil inventory studies indicate that moderate to light grazing does not negatively affect carbon stocks (Conant et al., 2001, 2017), and improving grazing management can augment carbon stocks (Chambers et al., 2016). Carbon cycle responses to woody encroachment are determined from inventories of carbon stocks in vegetation and soils in plots that have been experiencing woody encroachment for different periods of time (Barger et al., 2011; Knapp et al., 2008a).

Major uncertainties

Uncertainties in grazing management impacts on carbon cycling in grasslands stem mainly from the regional variations in soil carbon responses to management, from challenges in designing scientific studies that adequately represent real-world management practices, and from limitations faced when extrapolating plot-level studies to broader areas (Conant et al., 2017). Interactive effects of grazing, climate, soil type and plant community composition on carbon storage are not well constrained (McSherry and Ritchie 2013). The magnitude of carbon accumulation below ground in response to woody encroachment is poorly constrained, but change in carbon pools above ground is well known (Barger et al., 2011; Knapp et al., 2008a). Fire regimes are changing with increasing temperatures and altered vegetation; uncertainties in future fire risk add uncertainty to projections of carbon budgets.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is high confidence with general agreement across several studies that moderate to light grazing will not have a negative impact on carbon cycling.

Estimated likelihood of impact or consequence, including short description of basis of estimate

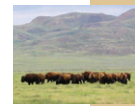
Woody encroachment likely will lead to increased carbon storage in mesic grasslands.

Summary sentence or paragraph that integrates the above information

Carbon likely will continue to accumulate for the next several decades in grasslands if they are appropriately managed.

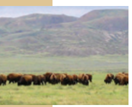
SUPPORTING EVIDENCE FOR TABLES

Table 10.1, p. 401, is based on Hayes et al. (2012). The areas for grasslands by countries and the continent are from the models and inventory analyses used in their study (see Table S10 in Hayes et al., 2012). The area for “Others” is smaller for the models than the inventory analysis mainly because the latter includes urban areas. Inventory estimates are the sum of livestock methane



(CH_4) emissions + livestock carbon dioxide (CO_2) emissions + grassland net ecosystem exchange (NEE) for Canada and the United States. Taiga was excluded from Canada grassland NEE and livestock emissions. For Mexico, the number for "Others" was used because extracting grassland NEE was not possible. Atmospheric inversion models (AIMs) and land-surface models (LSMs) are from Table 2 in Hayes et al. (2012) and do not include CH_4 emissions or human settlement emissions. Thus, the AIM values of NEE for "Others" should be representative of grassland and pastureland NEE. Area estimate for grasslands: www.statista.com/statistics/201761/projection-for-total-us-grassland-area-from-2010.

Table 10.2, p. 403. Carbon fluxes and stocks for grasslands and shrublands in the conterminous United States summarized from the LandCarbon project (landcarbon.org/categories). Values are averages of the A1B, A2, and B1 climate scenarios and estimated using the FOREcasting SCEnarios of land-use change (FORE-SCE) model and the Erosion-Deposition-Carbon-Model (EDCM), CENTURY, and PBN carbon models (Liu et al., 2012b, 2014; Zhu et al., 2011). Climate projections based on emissions scenarios used by the LandCarbon Project are considered to be similar to representative concentration pathway (RCP) scenarios (Knutti and Sedláček 2013). Negative fluxes indicate carbon losses from the ecosystem; positive fluxes indicate carbon gains by the ecosystem. The total flux is considered to be the net ecosystem carbon balance (NECB). Land-cover classification could be a source of differences. Flux towers mostly measure actual grassland and rangeland, whereas the General Ensemble Biogeochemical Modeling System (GEMS) includes both grassland and shrubland. The conterminous United States has about 1 million km^2 of grassland and 1.3 million km^2 of shrubland (from Liu et al. land-cover data). The area difference is notable. Land conversion to and from agriculture and permanent grassland loss to urban land all contribute to the total carbon number.



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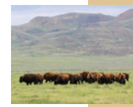

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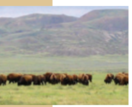

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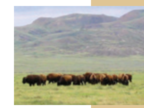

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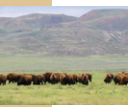

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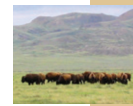

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