Projected Future Carbon Storage and Greenhouse-Gas Fluxes of Terrestrial Ecosystems in the Western United States

By Shuguang Liu, Yiping Wu, Claudia J. Young, Devendra Dahal, Jeremy M. Werner, Jinxun Liu, Zhengpeng Li, Zhengxi Tan, Gail L. Schmidt, Jennifer Oeding, Terry L. Sohl, Todd J. Hawbaker, and Benjamin M. Sleeter

Chapter 9 of

Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of the Western United States

Edited by Zhiliang Zhu and Bradley C. Reed

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Chapter 9. Projected Future Carbon Storage and Greenhouse-Gas Fluxes of Terrestrial Ecosystems in the Western United States

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9.1. Highlights

- On the basis of the land-use and land-cover (LULC) scenarios, climate-change projections, and biogeochemical models used in this assessment, the total carbon stored in the ecosystems of the Western United States in 2050 was projected to range from 13,743 to 19,407 TgC, an increase of 1,325 to 3,947 TgC from the mean baseline conditions (2001–2005; chapter 5 of this report). The amount of projected future potential carbon stored was highly variable among multiple model runs, ecoregions, and ecosystems.
    - The Western Cordillera ecoregion was projected to store the most carbon, accounting for 60 percent of the projected total stored carbon in Western United States, followed by the Cold Deserts (18 percent of the total), Marine West Coast Forest (10 percent), Mediterranean California (8 percent), and Warm Deserts (4 percent) ecoregions.
    - Among the different ecosystems, forests were projected to store the most carbon, accounting for 70 percent of the projected total carbon stored in the Western United States, followed by grasslands/shrublands (23 percent of the total), agricultural lands (6 percent), and other lands (1 percent).
    - About 80 percent of the projected total carbon storage was evenly distributed in aboveground live biomass and soil organic carbon in the top 20 centimeters of the soil layer, with the remaining 20 percent stored in dead biomass (forest litter and dead, woody debris).
- Between 2006 and 2050, and depending on the LULC scenarios, climate projections, and biogeochemical models used in this assessment, the mean annual net carbon flux was projected to range between −113.9 and 2.9 TgC/yr for the Western United States. (Negative values denote a carbon sink.) Compared to the baseline net carbon flux estimates (−162.9 to −13.6 TgC/yr; chapter 5 of this report), the future carbon-sequestration rates in the Western United States were projected to decline by 16.5 to 49 TgC/yr.
    - The Western Cordillera ecoregion was projected to be the largest carbon sink, accounting for 65 percent of the total carbon sequestered in the Western United States, followed by the Mediterranean California (17 percent of the total), the Cold Deserts (11 percent), and the Marine West Coast Forest (7 percent) ecoregions. The Warm Deserts ecoregion was projected to be either a minor carbon source or carbon neutral.
    - All of the major ecosystems modeled in the assessment were projected to gain more carbon than lose it to the atmosphere. The carbon uptake in forests was projected to account for 73 percent of the projected total sink, followed by agricultural lands (13 percent of the total), grasslands/shrublands (11 percent), wetlands (1 percent), and other lands (2 percent).
    - Of the total projected carbon sink, about 50 percent was projected to accumulate in live biomass, 44 percent was projected to accumulate in soil organic carbon, and the remaining 5 percent was projected to accumulate in dead biomass.

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- The Western United States was projected to be a weak sink for methane (−3.1 to −2.8 $TgCO_{2\text{-eq}}$/yr) and a weak source for nitrous oxide (1.6 to 1.7 $TgCO_{2\text{-eq}}$/yr); these results were similar to the baseline estimates (chapter 5 of this report). When combined with the projected net carbon fluxes (−113.9 to 2.9 TgC/yr, or −417.9 to 10.9 $TgCO_{2\text{-eq}}$/yr), the net total flux of these three greenhouse gases was projected to be −419 to 10 $TgCO_{2\text{-eq}}$/yr by 2050.

9.2. Introduction

The results of the terrestrial carbon storage and flux modeling for the baseline years (2001–2005) were introduced in chapter 5 of this report. This chapter presents the methods and results of assessing the projected amounts of carbon stored in terrestrial ecosystems and projected greenhouse-gas (GHG) fluxes. The task of modeling future carbon storage and flux projections is linked with land-use and land-cover (LULC) mapping and modeling (chapter 2), future LULC scenarios (chapter 6), future climate-change projections (chapter 7), and the projected future extent and severity of wildland fires (chapter 8). The relations between this chapter and the other chapters are depicted in figure 1.2 of chapter 1 of this report. The definitions of the ecosystems used in this assessment are found table 2.1 of chapter 2 of this report.

The atmospheric concentrations of the major GHGs—carbon dioxide (CO_2,), methane (CH_4,), and nitrous oxide (N_2O)—increased by 36, 148, and 18 percent, respectively, from 1750 (the pre-industrial era) to 2006, mainly because of increased human activities (Intergovernmental Panel on Climate Change, 2007). According to the most recent inventory provided by the U.S. Environmental Protection Agency (EPA, 2012), GHG emissions in the United States increased at an average rate of 0.5 percent per year since 1990, and the total emissions for the United States were 6,821.8 teragrams of carbon dioxide equivalent ($TgCO_{2\text{-eq}}$) in 2010, which was an increase of 213.5 $TgCO_{2\text{-eq}}$ (or 3 percent) over the 2009 level. This increase, as reported in EPA (2012), was principally attributed to an increase in energy consumption across all economic sectors and an increased demand for electricity induced by a warming period (especially warmer summers during this period in the United States).

Studies that used both atmospheric and ground-based methods agreed on the presence of a carbon sink in the conterminous United States (Houghton and others, 1999; Pacala and others, 2007; Pan, Birdsey, and others, 2011). A global carbon sink of approximately 2 to 6 petagrams of carbon per year (PgC/yr) was estimated for 1990 through 2100, and the variability of the sink depended on the emissions scenarios that were used in the studies (Levy and others, 2004). Projections of future carbon sources and sinks in the United States were highly variable (Bachelet and others, 2001, 2003; Hurtt and others, 2002). Hurtt and others (2002) suggested that a significant reduction in the sink may be possible during the 21st century and that the carbon sink in the United States would decline from 0.33 PgC/yr in the 1980s to 0.21 PgC/yr by 2050 to 0.13 PgC/yr by 2100. This modeled decline was based on the premise that the ecosystem recovery process that had been primarily responsible for the contemporary carbon sink in the United States would slow down over the 21st century. For temperate forests in the United States, recent studies yielded uncertain results. Heath and Birdsey (1993) estimated a smaller carbon sink during a projected period between 1987 and 2050 (average of 60 teragrams of carbon per year, or TgC/yr) than during the period between 1952 and1987 (average of 250 TgC/yr). On the basis of forest inventory data, Pan, Birdsey, and others (2011) determined that the United States' forests were a stronger carbon sink during the 2000s (94 grams of carbon per square meter per year, or $gC/m^2/yr$) than during the 1990s (72 $gC/m^2/yr$). According to Hurtt and others (2002), the existing carbon sink in the United States could become a source under the scenario of a failed wildland-fire-suppression effort, resulting in a loss of 20 PgC to the atmosphere during the 21st century. Smithwick and others (2002) suggested that the carbon-sequestration potential of the Pacific Northwest region could be much higher than the current rates. The National Forest Carbon Inventory Scenarios for the Pacific Southwest Region (California) indicated that the national forests may become a carbon source in the mid-21st century due to wildfire, disease, and other disturbances (Goines and Nechodom, 2009; U.S. Department of Agriculture (USDA) Forest Service, 2012a).

The purpose of this chapter is to report the estimated projections of carbon sequestration and GHG emissions reduction in the Western United States from 2006 to 2050. The input data and methods used in this chapter followed an overall assessment methodology (Zhu and others, 2010), which included climate-change projections; LULC-change projections; simulations of wildland-fire extent, severity, and emissions; and biogeochemical modeling of carbon dynamics and GHG fluxes.

9.3. Input Data and Methods

For the biogeochemical component of this assessment, the General Ensemble Biogeochemical Modeling System (GEMS) (S. Liu and others, 2012; S. Liu, 2009; chapter 5 of this report) was used to simulate the carbon sources and sinks and GHG fluxes in the Western United States. The modeling framework incorporated several biogeochemical models: the CENTURY model (Metherell and others, 1993), the Erosion-Deposition-Carbon Model (EDCM; S. Liu and others, 2003), and a spreadsheet model (Zhu and others, 2010). The input and output data layers used with these models were described in S. Liu and others (2009, 2011; chapters 4 and 5 of this

report). Examples of some of the specific input data are shown in figure 9.1 below. The GEMS was calibrated and validated extensively using net primary productivity data derived from the Moderate Resolution Imaging Spectroradiometer (MODIS NPP) and U.S. Department of Agriculture (USDA) grain yield information (chapter 5 of this report).

In order to explore the carbon dynamics and GHG emissions under a wide range of projected future conditions, 21 GEMS model runs were performed for the future projections. These runs were as follows:

- Three spreadsheet model runs. Each run represented carbon dynamics and GHG fluxes under an LULC scenario that was developed in accordance with storylines A1B, A2, or B1 from the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC–SRES; Nakicenovic and others, 2000; chapter 6 of this report). The spreadsheet model did not simulate the effects of climate change.
- Nine EDCM simulations. Each simulation was a unique combination of an LULC-change scenario corresponding to an IPCC–SRES storyline and a climate-change projection by a general circulation model (GCM). In this assessment, three IPCC–SRES scenarios (A1B, A2, and B1) were used (Sleeter, Sohl, Bouchard, and others, 2012) along with climate-change projections by three GCMs: Model for Interdisciplinary Research on Climate 3.2 medium resolution (MIROC 3.2–medres), Australia's Commonwealth Scientific and Industrial Research Organisation Mark 3.0 (CSIRO–Mk3.0), and The Third Generation Coupled Global Climate Model of the Canadian Centre for Climate Modelling and Analysis (CCCma CGCM3.1) (Joyce and others, 2011).
- Nine CENTURY model simulations. The setups for the CENTURY model runs were the same as for the EDCM.

As with the baseline model runs, a sampling strategy was used to improve overall modeling efficiency. The spreadsheet-model simulations were performed for all ecosystems at 250-m resolution; however, a 1 percent systematic sampling rate was used to accelerate the CENTURY model and and EDCM simulations for the Western United States. As noted in chapter 5 of this report, this sampling procedure was representative of the whole population (all pixels).

For the rest of the modeling process, the modeling architecture, initialization, and execution were the same as for the baseline years (chapter 5 of this report). Therefore, the rest of this chapter focuses on the methods and results that were relevant to the future projections. The key concepts and terminology used in this chapter, including net carbon flux, net primary production (NPP), net ecosystem production (NEP), and net ecosystem carbon balance (NECB), follow conventions used in the literature, as described in chapter 1 of this report.

9.4. Results and Discussion

9.4.1. Projected Carbon Stocks in 2050

Annual maps of total carbon stock in ecosystems from 2006 to 2050 were generated for the Western United States on the basis of the 21 simulation model runs described previously. As a result, there were 21 carbon stock maps for each year from 2006 to 2050. Figure 9.2 represents an average of the 21 annual maps and shows the spatial distribution of the average total amount of carbon (carbon in biomass plus SOC in the top 20 cm of the soil layer) stored in ecosystems in the Western United States in 2050 (the final year of the scenario period) and the standard deviation around the mean value for the 21 simulation model runs. The spatial pattern of stored carbon in 2050 was in general agreement with that of 2005 (chapter 5 of this report).

The projected minimum and maximum amounts of stored carbon from the 21 simulation model runs are provided in table 9.1, by carbon pool, ecosystem, and ecoregion in the Western United States for 2050. The overall total carbon stored in all five ecoregions was projected to range from approximately 13,743 to 19,406 TgC, compared to 12,418 to 15,460 TgC in 2005. Among the ecoregions, the Western Cordillera was projected to have the most carbon stored by 2050, accounting for 60 percent of the total carbon stored in the Western United States, followed by the Cold Deserts (18 percent of the total), Marine West Coast Forest (10 percent), Mediterranean California (8 percent), and Warm Deserts (4 percent) ecoregions. Among the different ecosystems, forests were projected to store the most carbon (70 percent) in the Western United States, followed by grasslands/shrublands (23 percent of the total), agricultural lands (6 percent), and other lands (1 percent). About 80 percent of the total carbon stored was projected to be equally allocated to the live biomass and SOC pools and the remaining 20 percent was projected to be stored in dead biomass (such as forest litter and dead, woody debris). The projected allocation was similar to the pattern of total carbon stored in the same pools in 2005 (chapter 5 of this report).

The projected average future carbon density (carbon stored per unit of area) of the ecosystems varied substantially across ecoregions (fig. 9.2*A* and table 9.1); ranging from high to low, they were forests (15.2 kilograms of carbon per square meter, or kgC/m^2), wetlands (9.0 kgC/m^2), agricultural lands (5.4 kgC/m^2), grasslands/shrublands (2.4 kgC/m^2), and other lands (0.6 kgC/m^2). Geographically, the projected average future carbon density in forests alone was distributed in the Marine West Coast Forest (24.7 kgC/m^2), Mediterranean California (20.7 kgC/m^2), Western Cordillera (15.4 kgC/m^2), Cold Deserts (7.9 kgC/m^2), and Warm Deserts (5.9 kgC/m^2) ecoregions. Similarly, the highest and lowest carbon densities for grasslands/shrublands were projected to be found in the Marine West Coast Forest (9.7 kgC/m^2) and the Warm Deserts (1.5 kgC/m^2). The projected carbon stored in 2050 is briefly described by ecoregion, below.

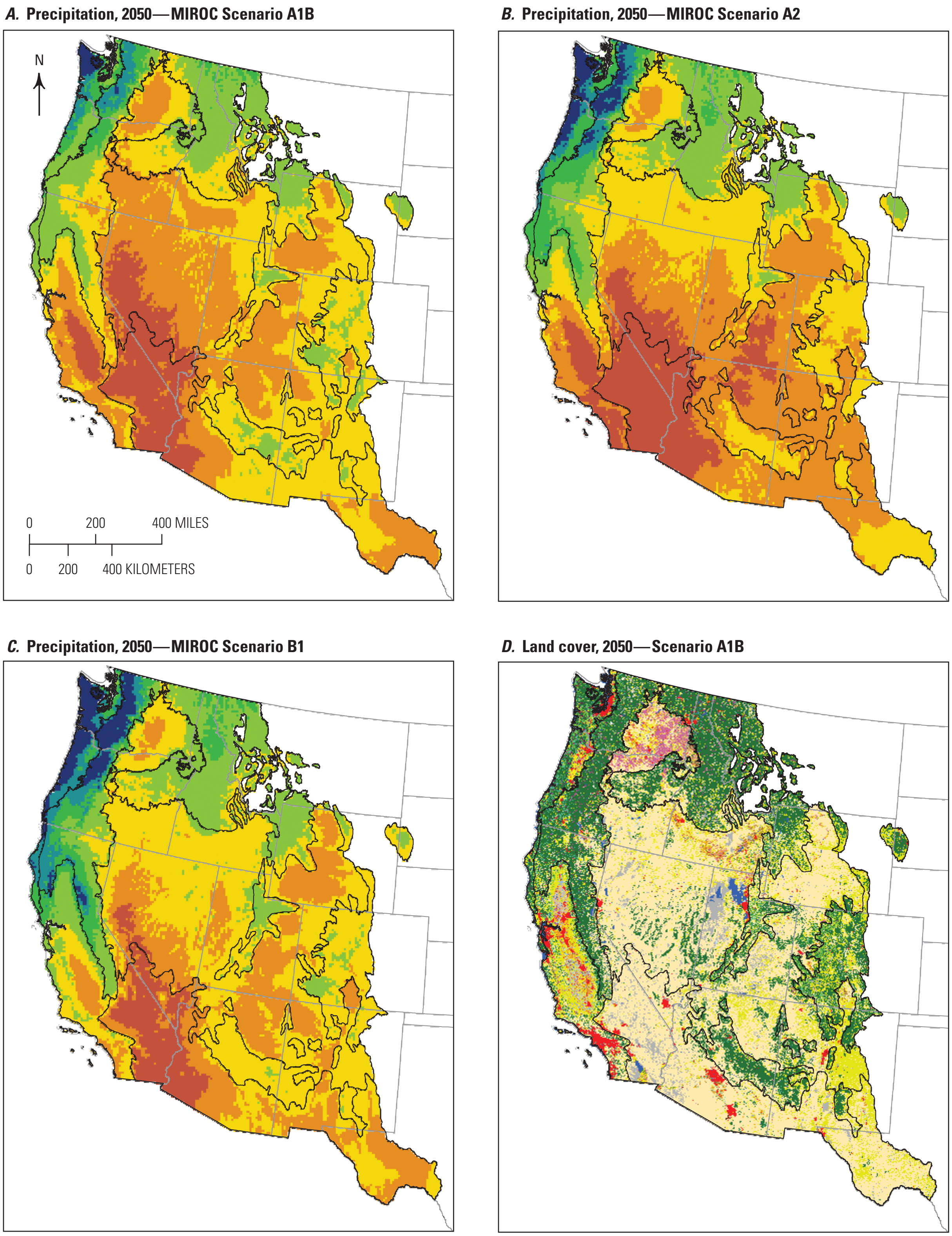

Figure 9.1. Maps showing projected total annual precipitation under the three IPCC–SRES scenarios and projected land cover under the A1B scenario in 2050. *A*, Projected total annual precipitation under the A1B scenario in 2050. *B*, Projected total annual precipitation under the A2 scenario in 2050. *C*, Projected total annual precipitation under the B1 scenario in 2050. *D*, Projected land use and land cover (LULC) map under the A1B scenario in 2050 in 2050. The precipitation data were projected by the MIROC 3.2–medres general circulation model (Joyce and others, 2011). The projected LULC change was from chapter 6 of this report with downscaling of agriculture to crop types by Schmidt and others (2011). IPCC–SRES, Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakicenovic and others, 2000); MIROC 3.2–medres, Model for Interdisciplinary Research on Climate 3.2 medium resolution.

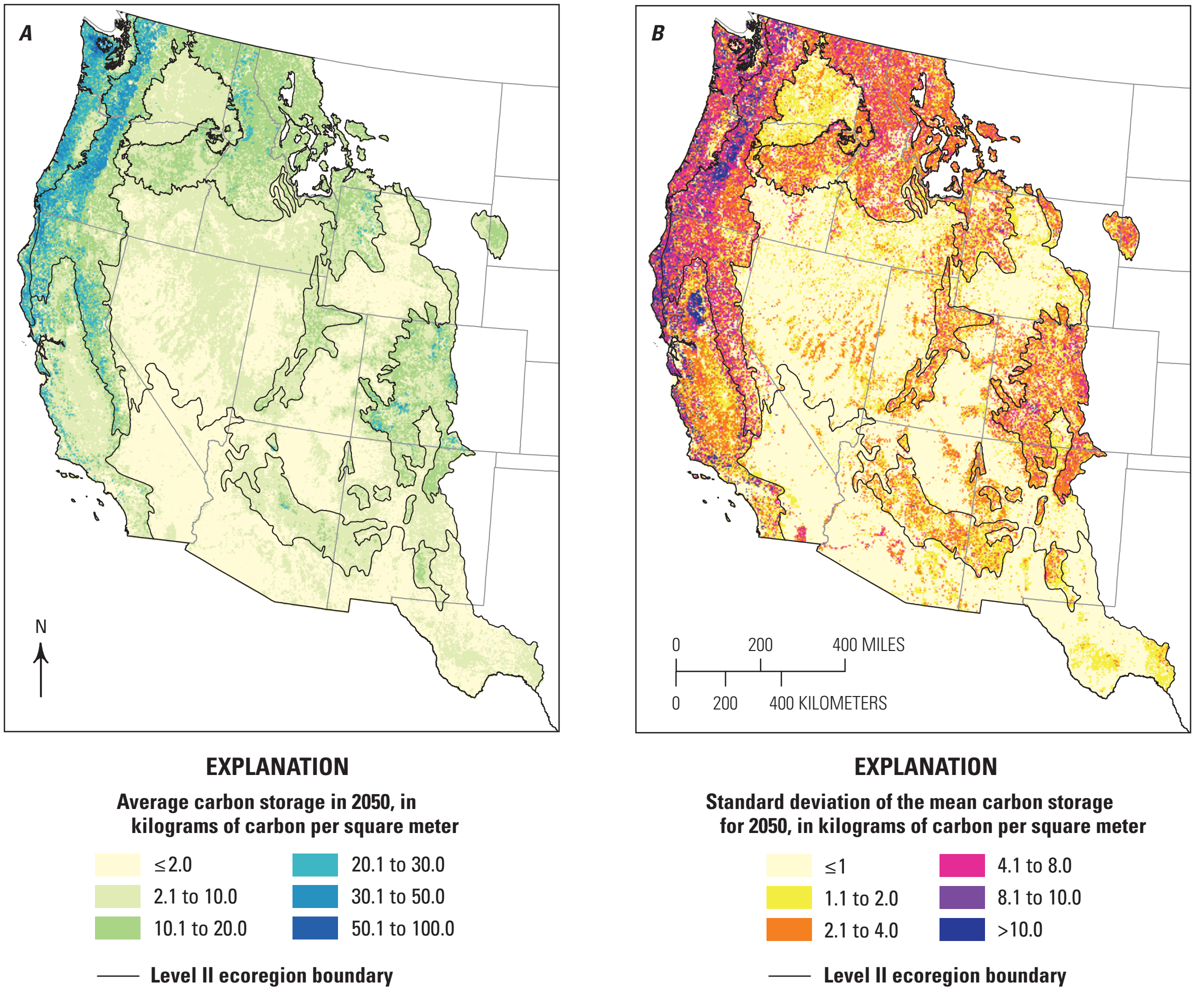

Figure 9.2. Maps showing the projected mean carbon stored and the standard deviation in 2050. *A*, Projected mean carbon stored in 2050 derived from 21 simulation model runs using three biogeochemical models (spreadsheet model, CENTURY model, and EDCM) under three IPCC–SRES scenarios (A1B, A2, and B1) and three general circulation models (MIROC 3.2–medres, CSIRO–MK3.0, and CCCma CGCM). *B*, The projected standard deviation around the mean of the 21 simulation model runs. CCCma CGCM3.1, The Third Generation Coupled Global Climate Model of the Canadian Centre for Climate Modelling and Analysis; CSIRO–Mk3.0, Australia's Commonwealth Scientific and Industrial Research Organisation Mark 3.0; EDCM, Erosion-Deposition-Carbon Model; IPCC–SRES, Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakicenovic and others, 2000); MIROC 3.2–medres, Model for Interdisciplinary Research on Climate 3.2 medium resolution.

9.4.1.1. Western Cordillera

The total carbon stored in the Western Cordillera ecoregion (the largest of the five ecoregions) was projected to range between approximately 8,703 and 10,670 TgC in 2050 (table 9.1). Live biomass, SOC, and deadmass were projected to store an average of 46, 32, and 22 percent of the total carbon, respectively. Among the different ecosystems, forests were projected to store the most carbon (average of 87 percent of the total) followed by grasslands/shrublands (12 percent). The carbon stored in agricultural lands, wetlands, and other lands (combined) was projected to be only 1 percent of the total carbon. The projected allocation of carbon varied substantially between the three pools (live biomass, soil organic carbon, and dead biomass) across ecosystems. Live biomass was projected to account for 51 percent of the total carbon stored in forests, which was more than the projected sum of the other two pools. In contrast, soil organic carbon was projected to be the dominant storage pool in 2050, holding 76, 86, 64, and 90 percent for grasslands/shrublands, agricultural lands, wetlands, and other lands, respectively.

9.4.1.2. Marine West Coast Forest

The estimated carbon stored in the Marine West Coast Forest in 2050 was projected to range from approximately 1,513 to 1,908 TgC (table 9.1). Live biomass and soil organic carbon were projected to contain 48 and 33 percent, respectively, of this total amount which was similar to the projected allocation pattern in the Western Cordillera. Among the different ecosystems, forests were projected to store the most carbon (91 percent of the projected total carbon), followed by agricultural lands (4.5 percent), and grasslands/shrublands (2.5 percent). The total carbon projected to be stored in wetlands and other lands accounted for only 2.4 percent of the projected total carbon stored in this ecoregion. The live biomass carbon pool was projected to contain the most carbon in both forests and wetlands, accounting for 52 and 46 percent of their totals, respectively, whereas the soil organic carbon pool was projected to be the largest for other ecosystems accounting for 75, 87, and 78 percent of the total carbon stored in grasslands/shrublands, agricultural lands, and other lands, respectively.

9.4.1.3. Cold Deserts

The estimated carbon stored in the Cold Deserts ecoregion was projected to range from approximately 2,260 to 4,060 TgC in 2050 (table 9.1). In contrast to the Western Cordillera and Marine West Coast Forest ecoregions, soil organic carbon was projected to be the primary carbon pool (accounting for 61 percent of the projected total amount of carbon), followed by live biomass (20 percent). Unlike the Western Cordillera and Marine West Coast Forest, grasslands/shrublands were projected to serve as the primary carbon storage pool (58 percent), followed by forests (26 percent) and agricultural lands (13.7 percent). The total percentage of carbon stored in wetlands and other lands was projected to be about 2 percent. Like the Western Cordillera and the Marine West Coast Forest ecoregions, live biomass was projected to serve as the major carbon pool in forests (52 percent of the total forests), but for the other ecosystems, most carbon was projected to be stored in the soil organic carbon pool, ranging from 69 percent (for grasslands/shrublands) to 98 percent (for other lands). The difference in the projected carbon allocation among ecosystems in the Cold Deserts ecoregion compared with that of the Western Cordillera and Marine West Coast Forest was most likely caused by the different projected land-cover fractions. The Cold Deserts ecoregion was projected to be dominated by grasslands and shrublands, and the Western Cordillera and Marine West Coast Forest ecoregions were projected to be dominated by forests.

9.4.1.4. Warm Deserts

The Warm Deserts ecoregion stored the least amount of carbon in 2005 (chapter 5 of this report). By 2050, this ecoregion was projected to still store the least amount of carbon of all the ecoregions, with projected estimates ranging from approximately 465 to 1,177 TgC from all simulation runs (table 9.1). The projected allocation of carbon across the various ecosystems in the Warm Deserts was similar to that of the the Cold Deserts because of the similarities in ecosystem composition and processes. Like the Cold Deserts ecoregion (although much smaller in extent), soil organic carbon was projected to be the primary carbon pool by storing 63 percent of the total carbon, and live biomass was projected to store only 23 percent. Grasslands/shrublands were projected to store the most carbon (84 percent of the total), followed by agricultural lands (7.3 percent) and forests (6.9 percent). Live biomass was projected to account for 58 percent of the total carbon stock in forests, and soil organic carbon was projected to be the primary pool in grasslands/shrublands (64 percent), agricultural lands (82 percent), wetlands (41 percent), and others lands (97 percent).

9.4.1.5. Mediterranean California

For the Mediterranean California ecoregion, the total carbon stored in 2050 was projected to range from 801.5 to 1,591.2 TgC (table 9.1). Soil organic carbon was projected to be the primary carbon pool (storing 49 percent of the total carbon) and live biomass was projected to store 33 percent. The majority of the stored carbon was projected to be in forests (48.5 percent of the total) across all scenarios, followed by grasslands/shrublands (26 percent) agricultural lands (22 percent), and other lands (less than 1 percent). As with other ecoregions, live biomass was projected to be the primary

Table 9.1. Minimum and maximum projections of carbon stored in in the Western United States in 2050, based on 21 simulation model runs, by ecosystem and ecoregion.

[Only soil organic carbon (SOC) in the top 20 cm of the soil layer was calculated. Numbers may not sum due to rounding. km^2, square kilometers; max, maximum; min, minimum; TgC, teragrams of carbon or 10^{12} grams of carbon]

Ecoregion	Ecosystem	Area (km^2)	Live biomass (TgC)		Soil organic carbon (TgC)		Dead biomass (TgC)		Total (TgC)	
			Min	Max	Min	Max	Min	Max	Min	Max
Western Cordillera	Forests	545,522	3,980.7	4,649.6	1,592.7	2,577.4	1,696.6	2,353.1	7,874.3	9,002.6
	Grasslands/shrublands	274,643	72.3	146.9	616.4	1,023.8	0.0	277.8	731.0	1,446.5
	Agricultural lands	18,338	0.2	4.3	64.1	97.8	0.0	20.8	66.7	119.6
	Wetlands	3,531	6.5	8.3	12.2	32.1	2.4	8.6	24.4	47.7
	Other lands	30,234	0.2	2.2	5.5	53.9	0.0	2.6	7.3	54.1
	Total	872,268	4,060.0	4,811.4	2,290.9	3,785.1	1,699.0	2,662.9	8,703.6	10,670.4
Marine West Coast Forest	Forests	61,889	699.6	953.9	375.7	508.9	249.5	367.0	1,411.2	1,710.9
	Grasslands/shrublands	4,347	1.6	6.4	18.0	36.0	0.0	7.9	19.5	47.2
	Agricultural lands	10,342	0.3	4.7	56.2	74.2	0.0	14.6	57.9	89.6
	Wetlands	575	3.6	5.2	3.1	5.4	0.6	1.7	7.3	12.3
	Other lands	18,259	0.0	5.8	10.4	48.0	0.0	7.3	16.9	48.0
	Total	95,411	705.1	976.0	463.3	672.6	250.1	398.5	1,512.9	1,907.9
Cold Deserts	Forests	97,202	332.9	501.6	159.9	290.9	114.9	234.8	674.6	987.4
	Grasslands/shrublands	794,594	208.8	370.0	962.9	1,625.8	0.0	540.4	1,321.5	2,458.3
	Agricultural lands	87,191	0.1	17.4	221.6	421.9	0.0	87.6	235.8	509.8
	Wetlands	4,401	2.3	5.2	13.2	34.5	2.0	8.0	21.5	45.3
	Other lands	72,666	0.0	1.1	6.7	59.5	0.0	0.3	6.8	59.5
	Total	1,056,055	544.1	895.3	1,364.3	2,432.6	116.9	871.0	2,260.2	4,060.3
Warm Deserts	Forests	8,045	21.0	34.1	6.7	15.6	6.5	21.5	38.1	62.7
	Grasslands/shrublands	397,311	91.0	191.6	276.9	598.0	0.0	210.3	411.1	991.8
	Agricultural lands	11,700	0.0	2.4	10.8	78.6	0.0	15.4	12.9	95.7
	Wetlands	322	0.3	0.5	0.3	2.0	0.1	2.1	0.9	4.6
	Other lands	47,907	0.0	0.7	2.0	22.3	0.0	0.3	2.1	22.3
	Total	465,285	112.2	229.5	296.6	716.4	6.6	249.6	465.0	1,177.0
Mediterr-anean California	Forests	29,830	361.0	405.6	56.5	158.5	119.5	128.4	557.9	686.4
	Grasslands/shrublands	65,480	23.5	43.0	103.2	296.6	0.0	81.9	126.7	414.0
	Agricultural lands	40,799	0.0	8.1	88.8	341.2	0.0	65.0	96.3	413.9
	Wetlands	1,019	0.6	1.9	4.0	18.2	0.5	4.5	5.6	22.6
	Other lands	32,327	0.0	2.8	14.7	54.4	0.0	0.6	15.0	54.4
	Total	169,455	385.2	461.4	267.2	868.9	119.9	280.4	801.5	1,591.2
Western United States (total)	Forests	742,488	5,395.2	6,544.9	2,191.5	3,551.4	2,187.0	3,104.8	10,556.0	12,449.9
	Grasslands/shrublands	1,536,375	397.2	758.0	1,977.4	3,580.0	0.0	1,118.3	2,609.8	5,357.8
	Agricultural lands	168,371	0.7	37.0	441.4	1,013.7	0.0	203.4	469.6	1,228.5
	Wetlands	9,847	13.3	21.2	32.7	92.3	5.5	24.8	59.6	132.4
	Other lands	201,393	0.2	12.5	39.2	238.1	0.0	11.1	48.2	238.3
	Total	2,658,474	5,806.7	7,373.5	4,682.2	8,475.5	2,192.5	4,462.4	13,743.2	19,406.8

carbon pool for forests, accounting for 61 percent of the total carbon stored in forests, whereas in other ecosystems, most carbon was projected to be stored in the soil organic carbon pool, ranging from 73 percent in grassslands/shrublands to 95 percent in other lands.

9.4.2. Projected Future Net Ecosystem Carbon Fluxes Between 2006 and 2050

The projected future annual net carbon fluxes (or net ecosystem carbon balance (NECB)) between 2006 and 2050 were calculated as the difference in carbon stock between two consecutive years. A mean annual NECB was derived by averaging all 21 simulation model runs from 2006 to 2050. The standard deviation of the 21 model runs over the simulation time period was also calculated. The resulting models are depicted by the two maps shown in figure 9.3. Figure 9.3*A* indicates that the projected high levels of carbon sequestration (negative NECB, shown by green hues on the map) were strongly associated with the presence of forest ecosystems and that simulated disturbances, such as clearcutting in the Pacific Northwest, were projected to be responsible for a large number of carbon-release hot spots (positive NECB, indicated by red hues on the map). Carbon sequestration was also projected to occur in the agricultural lands of the Central California Valley and the Columbia Plateau level III ecoregions. The mean annual NECB was projected to be minimal in the majority of arid lands of the Western United States. The standard deviation map was spatially similar to the pattern of the mean annual NECB, and the spread was projected to be generally greater in areas with higher mean annual NECB value or higher carbon sequestration.

The projected minimum and maximum mean annual NECB values—from the 21 simulations and averaged annually between 2006 and 2050—are provided in table 9.2 by carbon pool, ecosystem, and ecoregion in the Western United States. The mean annual NECB values listed in this table represent the projected net carbon gain or loss after harvesting (timber and grain harvest) and wildland-fire emissions. The mean annual NECB estimates were projected to vary between −113.9 and 2.9 TgC/yr in the Western United States, which generally agrees with a projected increase in future carbon gains that has been documented elsewhere (Bachelet and others, 2001; J.E. Smith and Heath, 2008).

As shown in table 9.2, the mean annual NECB in the ecoregions of the Western United States was projected to be highly variable. Although the Western Cordillera ecoregion was projected to maintain the greatest carbon sink in the Western United States (accounting for 65 percent of the total mean annual NECB), other ecoregions were projected either to have smaller shares of the total mean annual NECB or to fluctuate between the carbon sink and source. Indeed, this was the case for the entire Western United States, with the overall mean NECB from the 21 model runs projected to vary between −113.9 and 2.9 TgC/yr. When compared with the estimated range of the mean annual NECB during the baseline years (−162.9 to −13.6; see chapter 5 of this report), the projected future mean annual NECB for the entire assessment region was down by 16.5 to 49 TgC/yr. Among all ecosystems, forests were projected to remain strong terrestrial carbon sinks, accounting for approximately 73 percent of the projected total mean NECB. The other ecosystems also were projected to have the potential to sequester carbon, but the interannual variability between carbon sinks or sources was projected to be high. On average, about 50 percent of the total carbon was projected to accumulate in live biomass, 44 percent in soil organic carbon, and the remaining 5 percent in dead biomass (forest litter and dead, woody debris). Wetlands were projected to have the highest mean annual NECB per unit of area (−57 $gC/m^2/yr$), compared with forests (−50 $gC/m^2/yr$), agricultural lands (−40 $gC/m^2/yr$), grasslands/shrublands (−3.9 $gC/m^2/yr$), and other lands (−3.5 $gC/m^2/yr$). The projected carbon sequestration rate per unit of area by forests in the Western United States was lower than the estimate of 75 $gC/m^2/yr$ for 2007 by D.P. Turner, Gockede, and others (2011). The simulated carbon-sequestration rate in agricultural lands was higher than the estimate of 19 $gC/m^2/yr$ by Kroodsma and Field (2006). Detailed descriptions for each ecoregion are given below.

9.4.2.1. Western Cordillera

In the Western Cordillera ecoregion, the projected mean annual NECB between 2006 to 2050 ranged from −61.9 to −6.7 TgC/yr (table 9.2). Among the different ecosystems, forests were projected to gain −27.9 TgC/yr (86 percent of the total), averaged across all model runs, followed by grasslands/shrublands with 3.9 TgC/yr (11 percent of the total), and the sum of the rest of the ecosystems at −0.9 TgC/yr (2.8 percent of the total).

9.4.2.2. Marine West Coast Forest

The projected mean annual NECB in the Marine West Coast Forest ecoregion between 2006 to 2050 ranged from −9.5 TgC/yr (a sink) to 1.8 TgC/yr (a source) (table 9.2), depending on which LULC scenarios, climate-change projections, or biogeochemical models were used. The projected mean annual NECB for forests in this ecoregion was –2.4 TgC/yr (or 73 percent of the total) across all model runs, followed by grasslands/shrublands (–0.3 TgC/yr) and agricultural lands (–0.2 TgC/yr). Wetlands and other lands were projected to account for −0.4 TgC/yr, or 12 percent of the total mean annual NECB.

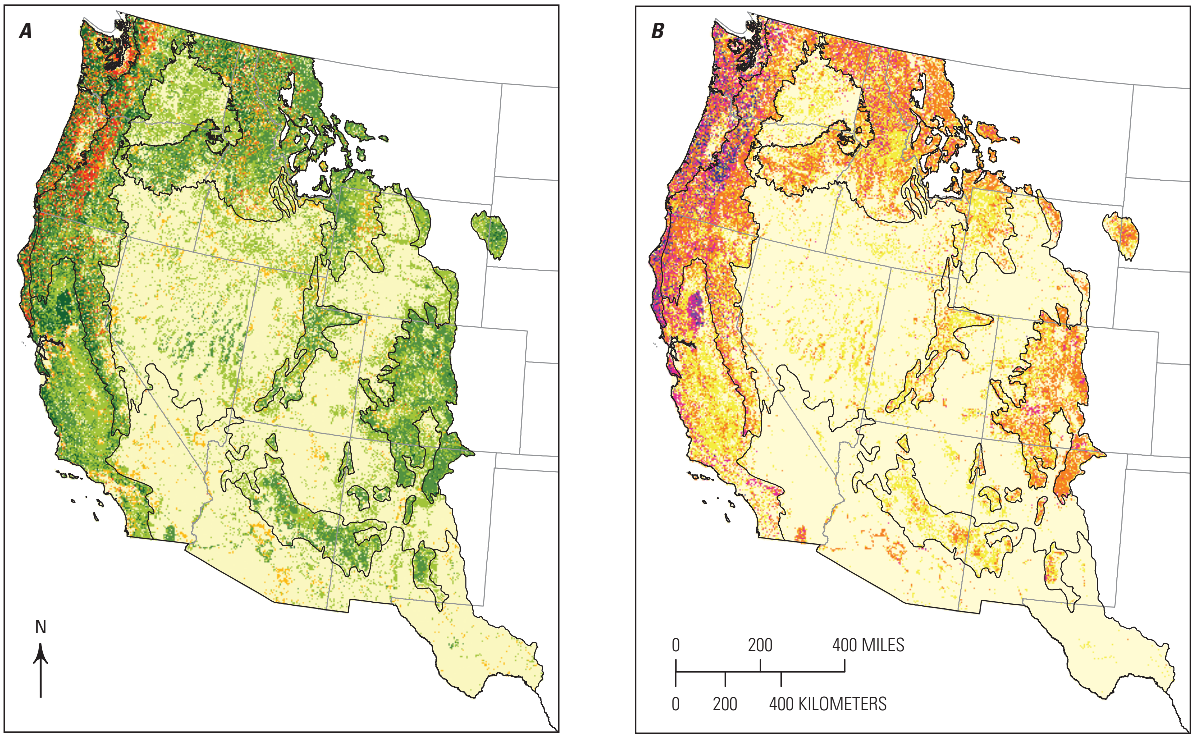

Figure 9.3. Maps showing the projected mean annual net ecosystem carbon balance (NECB), averaged annually from 2006 to 2050, and the standard deviation. *A*, Projected mean annual NECB derived from 21 simulation model runs using three biogeochemical models (spreadsheet model, CENTURY model, and EDCM), three IPCC–SRES scenarios (A1B, A2, and B1) and three general circulation models (MIROC 3.2–medres, CSIRO–MK3.0, and CCCma CGCM). Negative mean annual NECB values indicate projected carbon sinks or carbon gains by terrestrial ecosystems, and positive values denote projected carbon losses. *B*, The projected standard deviation around the mean of the 21 simulation model runs between 2006 and 2050. CCCma CGCM3.1, The Third Generation Coupled Global Climate Model of the Canadian Centre for Climate Modelling and Analysis; CSIRO–Mk3.0, Australia's Commonwealth Scientific and Industrial Research Organisation Mark 3.0; EDCM, Erosion-Deposition-Carbon Model; IPCC–SRES, Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakicenovic and others, 2000); MIROC 3.2–medres, Model for Interdisciplinary Research on Climate 3.2 medium resolution.

Table 9.2. The projected minimum and maximum mean net ecosystem carbon balance (NECB) values simulated in 21 model runs and averaged between 2006 and 2050, by ecoregion and ecosystem in the Western United States.

[Negative NECB values indicate carbon uptake or sequestration by ecosystems. Only soil organic carbon (SOC) in the top 20 cm of the soil layer was calculated. Numbers may not sum due to rounding. km^2, square kilometers; max, maximum; min, minimum; TgC, teragrams of carbon or 10^{12} grams of carbon]

Ecoregion	Ecosystem	Area (km^2)	Carbon net flux (TgC/yr)							
			Live biomass		Soil organic carbon		Dead biomass		Total	
			Min	Max	Min	Max	Min	Max	Min	Max
Western Cordillera	Forests	545,522	−28.6	−6.5	−15.3	0.1	−8.4	4.5	−52.3	−7.0
	Grasslands/shrublands	274,643	−0.7	0.5	−6.8	0.3	−1.2	0.0	−7.9	0.3
	Agricultural lands	18,338	0.0	0.0	−0.7	0.0	−0.3	0.0	−1.0	0.0
	Wetlands	3,531	−0.1	0.0	−0.3	0.0	−0.1	0.0	−0.4	0.0
	Other lands	30,234	0.0	0.0	−0.2	0.1	0.0	0.0	−0.2	0.0
	Total	872,268	−29.5	−6.0	−23.4	0.6	−10.0	4.5	−61.9	−6.7
Marine West Coast Forest	Forests	61,889	−5.0	0.9	−2.1	0.5	−1.0	0.3	−8.1	1.8
	Grasslands/shrublands	4,347	−0.1	0.0	−0.3	0.0	0.0	0.0	−0.4	0.0
	Agricultural lands	10,342	−0.1	0.0	−0.3	0.2	−0.2	0.0	−0.5	0.2
	Wetlands	575	−0.1	0.0	0.0	0.0	0.0	0.0	−0.1	0.0
	Other lands	18,259	−0.1	0.0	−0.4	−0.1	−0.1	0.0	−0.5	−0.1
	Total	95,411	−5.3	0.9	−3.1	0.6	−1.3	0.3	−9.5	1.8
Cold Deserts	Forests	97,202	−4.6	−0.9	−1.7	0.6	−1.4	0.8	−7.7	−0.8
	Grasslands/shrublands	794,594	−0.7	3.3	−9.7	0.7	−0.5	3.8	−8.7	4.5
	Agricultural lands	87,191	−0.1	0.0	−3.7	0.0	−1.0	0.0	−4.7	0.0
	Wetlands	4,401	0.0	0.0	−0.3	0.0	−0.1	0.0	−0.4	0.0
	Other lands	72,666	0.0	0.0	−0.2	0.1	0.0	0.0	−0.2	0.1
	Total	1,056,055	−5.4	2.4	−15.7	1.5	−2.9	4.6	−21.8	3.8
Warm Deserts	Forests	8,045	−0.3	0.0	−0.1	0.0	−0.1	0.1	−0.5	0.0
	Grasslands/shrublands	397,311	0.0	2.3	−4.0	0.6	−0.1	2.5	−3.9	5.4
	Agricultural lands	11,700	0.0	0.0	−1.2	0.0	−0.2	0.0	−1.3	0.0
	Wetlands	322	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	0.0
	Other lands	47,907	0.0	0.0	−0.1	0.1	0.0	0.0	−0.1	0.0
	Total	465,285	−0.3	2.3	−5.4	0.7	−0.4	2.6	−5.9	5.4
Mediterranean California	Forests	29,830	−3.4	−1.8	−1.6	0.0	−0.8	−0.1	−5.8	−2.0
	Grasslands/shrublands	65,480	−0.3	0.1	−2.6	0.5	−0.4	0.0	−3.0	0.6
	Agricultural lands	40,799	0.0	0.0	−4.3	0.1	−0.7	0.0	−5.0	0.1
	Wetlands	1,019	0.0	0.0	−0.3	0.0	−0.1	0.0	−0.3	0.0
	Other lands	32,327	−0.1	0.0	−0.5	−0.1	0.0	0.0	−0.5	−0.2
	Total	169,455	−3.9	−1.7	−9.3	0.5	−2.0	0.0	−14.7	−1.4
Western United States (total)	Forests	742,488	−42.0	−8.2	−20.9	1.3	−11.7	5.7	−74.4	−8.0
	Grasslands/shrublands	1,536,375	−1.7	6.1	−23.3	2.1	−2.3	6.3	−23.9	10.8
	Agricultural lands	168,371	−0.3	0.0	−10.3	0.3	−2.3	0.0	−12.6	0.3
	Wetlands	9,847	−0.2	−0.1	−1.0	0.1	−0.2	0.0	−1.4	0.0
	Other lands	201,393	−0.2	0.0	−1.5	0.0	−0.2	0.0	−1.5	−0.1
	Total	2,658,474	−44.4	−2.1	−57.0	3.9	−16.7	12.0	−113.9	2.9

9.4.2.3. Cold Deserts

The projected mean annual NECB in the Cold Deserts ecoregion between 2006 to 2050 ranged from −21.8 to 3.8 TgC/yr (table 9.2) across all model runs. The projected variability was represented by both forests and agricultural lands, each with 45 percent of the total mean annual NECB.

9.4.2.4. Warm Deserts

The projected mean annual NECB in the Warm Deserts ecoregion between 2006 to 2050 ranged from −5.9 to 5.4 TgC/yr (table 9.2). Among all the ecoregions, this ecoregion was projected to be the only carbon source, with a mean carbon emission of 0.3 TgC/yr. The dominant ecosystem in the ecoregion, grasslands/shrublands, was projected to contribute about 1 TgC/yr in emissions, whereas forests and agricultural lands combined were projected to account for −0.7 TgC/yr.

9.4.2.5. Mediterranean California

The projected mean annual NECB in the Mediterranean California ecoregion between 2006 and 2050 ranged from −14.7 to −1.4 TgC/yr, of which forests were projected to accumulate the most carbon (−3.7 TgC/yr or 42 percent of the total), followed by agricultural lands (−2.8 TgC/yr) and grasslands/shrublands (−1.9 TgC/yr). Wetlands and other lands were each projected to accumulate about –0.1 TgC/yr, or 1 percent of the total mean annual NECB in this region.

9.4.3. Variability in the Projected Mean Carbon Stock and Mean Net Ecosystem Carbon Balance

As noted previously, 21 simulation model runs were conducted. The objective was to project a range of estimates for the amount of carbon stored and the NECB in order to assess the future carbon storage and sequestration capacities in the region. The variability in the ranges of the resulting estimates represents a major portion of the uncertainty in the assessment results. Table 9.3 compares the projected estimates of mean carbon stocks in 2050 and the mean annual NECB from 2006 to 2050. The data were derived by averaging all of the combinations of the 21 model runs for each ecosystem, for each of the five ecoregions, and for the entire Western United States. A variability value was also calculated as a percent measure for each of the three subsets of the model runs by dividing the range of the minimum and maximum estimates of the subset by their mean, and multiplying by 100.

Among the three biogeochemical models, the EDCM and the spreadsheet model performed similarly, whereas the CENTURY model consistently led to a higher projected estimate of stored carbon than the other two. The models performed differently across ecoregions with the smallest discrepancy found in the Marine West Coast Forest (6 percent variability across three models) and the highest in the Warm Deserts (58 percent). For the projected mean annual NECB estimates, the CENTURY model almost always yielded the highest estimates, followed by the EDCM, and the spreadsheet model (table 9.3). The variability among the models in projecting the mean annual NECB was very high, ranging from 129 percent in the Cold Deserts to 258 percent in the Warm Deserts, suggesting that future effort should be directed to investigating the causes of the divergence of the models and reducing the models' uncertainties.

The variability in the projected carbon stock estimates among the three LULC scenarios was small, ranging from 1 to 9 percent across the ecoregions (table 9.3). The variability of in the projected mean annual NECB under these scenarios was relatively higher than that of the carbon stock, ranging from 4 percent in the Mediterranean California to 200 percent in the Warm Deserts. The higher variability of the projected mean annual NECB across scenarios in some ecoregions did not necessarily indicate that there was a big difference among the results of the scenario modeling. The high variability may have been simply related to the low projected mean annual NECB estimates in the arid regions and how the percent variability was defined. Overall, the projected estimates of carbon stock and mean annual NECB were not significantly affected by the GCMs (table 9.3), with variability ranging from 0.4 to 25 percent for projected carbon stocks and from 3 to 1,139 percent for the projected mean annual NECB. Again, the large relative variability was associated with the low projected mean annual NECB. The projected mean annual NECB varied from −62.2 TgC/yr under the CSIRO–Mk3.0 model to −51.2 TgC/yr under the MIROC 3.2–medres model.

9.4.4. Projected Future Greenhouse-Gas Fluxes from 2006 to 2050

For this assessment, carbon dioxide (CO_2) fluxes were simulated by the EDCM and the CENTURY model as part of the carbon flux assessment described in the previous section of this chapter, whereas methane (CH_4) and nitrous oxide (N_2O) fluxes were simulated separately by the spreadsheet model. To calculate the global warming potential (GWP) in carbon dioxide equivalent ($CO_{2\text{-eq}}$), a factor of 21 was used for methane and of 310 for nitrous oxide (EPA, 2003). The uptake of GWP indicates that GHG fluxes into ecosystems were greater than fluxes out of ecosystems. The projected minimum and maximum mean annual fluxes and their total GWP for 2006 to 2050 are listed by ecoregion and ecosystem in table 9.4. Note that these flux estimates did not include the wildland-fire emission estimates presented in chapter 8 of this report and that the climate-change projections (using GCMs) were not considered in modeling the methane and nitrous oxide fluxes.

Table 9.3. Comparison of projected mean carbon stocks in 2050 and projected mean annual net ecosystem carbon balance from 2006 to 2050, and their percent variability, derived from combinations of three biogeochemical models, three land-use and land-change scenarios, and three general circulation models for each of the five ecoregions and for the entire Western United States.

[EDCM, Erosion-Deposition-Carbon Model; NA, not applicable; NECB, net ecosystem carbon balance; TgC, teragrams of carbon; TgC/yr, teragrams of carbon per year]

	Projected mean carbon stock in 2050 (TgC)						Projected mean annual NECB from 2006 to 2050 (TgC/yr)					
	Western Cordillera	Marine West Coast Forest	Cold Deserts	Warm Deserts	Mediterranean California	Western United States (total)	Western Cordillera	Marine West Coast Forest	Cold Deserts	Warm Deserts	Mediterranean California	Western United States (total)
Biogeochemical models												
CENTURY	10,302.1	1,744.7	3,402.7	898.6	1,495.0	17,843.1	−54.1	−6.0	−7.7	0.3	−12.8	−80.3
EDCM	9,217.6	1,637.5	2,583.1	510.6	1,186.2	15,135.1	−18.9	−1.7	−5.3	0.4	−7.2	−32.8
Spreadsheet	8,874.0	1,653.3	2,429.1	586.7	849.6	14,392.7	−9.7	−0.5	−1.5	−0.1	−1.9	−13.6
Variability	15	6	35	58	55	22	161	204	129	258	148	158
Land-use and land-change scenarios												
A1B	9,540.0	1,631.1	2,909.8	678.8	1,261.1	16,020.8	−30.6	−2.2	−5.8	0.5	−8.6	−46.7
A2	9,615.1	1,648.1	2,902.2	681.0	1,273.6	16,120.1	−32.3	−2.5	−5.6	0.4	−8.9	−48.9
B1	9,744.8	1,777.9	2,925.1	703.5	1,276.7	16,428.0	−35.2	−5.4	−6.1	−0.1	−9.0	−55.7
Variability	2	9	1	4	1	3	14	97	9	200	4	18
General circulation models												
CCCma CGCM	9,772.1	1,699.2	2,979.3	682.0	1,342.7	16,475.2	−36.8	−4.0	−6.2	0.8	−10.0	−56.2
CSIRO–Mk3,0	9,775.0	1,682.7	3,138.2	802.2	1,345.6	16,743.7	−36.8	−3.7	−9.8	−1.8	−10.1	−62.2
MIROC 3.2–medres	9,732.5	1,691.5	2,861.2	629.6	1,333.6	16,248.4	−35.9	−3.9	−3.6	2.0	−9.8	−51.2
Variability	0	1	9	25	1	3	3	10	94	1,139	3	19
All combinations												
Minimum	9,062.1	1,580.6	2,468.4	479.2	1,172.2	NA	−60.9	−8.6	−18.4	−5.8	−13.3	NA
Maximum	10,606.9	1,862.0	3,882.4	1,169.5	1,520.5	NA	−15.5	−0.4	0.5	4.1	−6.9	NA
Overall variability	16	17	47	98	26	NA	−124	−212	−290	2,937	−64	NA

The Western United States was generally projected to incur low levels of methane and nitrous oxide fluxes annually over the projection period of 2006 to 2050, which was similar to the baseline years of 1992 to 2005. As presented in chapter 5, the baseline estimates for methane and nitrous oxide ranged from −3.1 to −2.9 $TgCO_{2\text{-eq}}$/yr and from 1.7 to 1.7 $TgCO_{2\text{-eq}}$/yr, respectively, for the two gases. In comparison, the projected future methane and nitrous oxide fluxes, in comparison, ranged from −3.1 to −2.8 and from 1.63 to 1.68 $TgCO_{2\text{-eq}}$/yr, respectively, which indicates virtually no change over the two periods of the assessment. When combined with the projected net carbon dioxide fluxes for 2006 to 2050, which ranged from −418 to 11 $TgCO_{2\text{-eq}}$/yr, the total resulting GWP for the Western United States was projected to range from −419 to 9.8 $TgCO_{2\text{-eq}}$/yr. The details of methane and nitrous oxide fluxes by ecoregion are described below.

9.4.4.1. Western Cordillera

The mean annual GWP of the Western Cordillera ecoregion between 2006 and 2050 was projected to range from −227.9 to −25.1 $TgCO_{2\text{-eq}}$/yr (table 9.4). The mean methane uptake in this ecoregion was projected to be −1.3 $TgCO_{2\text{-eq}}$/yr with the highest contribution from forests (−0.89 $TgCO_{2\text{-eq}}$/yr) and grasslands/shrublands (−0.81 $TgCO_{2\text{-eq}}$/yr). The rate of methane emissions in wetlands was projected to be 0.40 $TgCO_{2\text{-eq}}$/yr. The mean annual emission of nitrous oxide was projected to be 0.58 $TgCO_{2\text{-eq}}$/yr, of which forests and grasslands/shrublands contributed 52 percent and 40 percent, respectively.

9.4.4.2. Marine West Coast Forest

The mean annual GWP of the Marine West Coast Forest ecoregion between 2006 and 2050 was projected to range from −34.42 to 7.11 $TgCO_{2\text{-eq}}$/yr (table 9.4), depending on the model runs. Most of the uptake was due to the projected future carbon sequestration in the region, which was estimated to sequester the most carbon among all ecoregions on a per-unit-area basis. The methane and nitrous-oxide fluxes were projected to continue to remain emission-neutral.

9.4.4.3. Cold Deserts

The mean annual GWP of the Cold Deserts ecoregion between 2006 and 2050 was projected to range from −81.89 to 12.23 $TgCO_{2\text{-eq}}$/yr (table 9.4). The mean methane uptake was projected to be about −2 $TgCO_{2\text{-eq}}$/yr with contributions from grasssslands/shrublands (−2.77 $TgCO_{2\text{-eq}}$/yr), forests (−0.42 $TgCO_{2\text{-eq}}$/yr), and agricultural lands (−0.06 $TgCO_{2\text{-eq}}$/yr). Wetlands and other lands were projected to emit about 1.2 $TgCO_{2\text{-eq}}$/yr of methane. The mean emission of nitrous oxide was 0.40 $TgCO_{2\text{-eq}}$/yr, of which grasslands/shrublands and agricultural lands contributed about 47 percent and 34 percent, respectively.

9.4.4.4. Warm Deserts

The mean annual GWP of the Warm Deserts ecoregion between 2006 and 2050 was projected to range from −22.32 to 19.5 $TgCO_{2\text{-eq}}$/yr (table 9.4). The methane and nitrous oxide fluxes were projected to remain emission-neutral.

9.4.4.5. Mediterranean California

The mean annual GWP of the Mediterranean California ecoregion between 2006 and 2050 was projected to range from −53.68 to −3.88 $TgCO_{2\text{-eq}}$/yr (an overall sink; table 9.4). In a separate study, the major GHG fluxes in forests of the State of California in recent years (2000–2006) were estimated to be −10.7 $TgCO_{2\text{-eq}}$/yr (California Environmental Protection Agency Air Resources Board, 2009). The projected mean annual emissions of methane and nitrous oxide remained low compared to the carbon sink in the ecoregion. Forests and grasslands/shrublands were projected to sequester methane (−0.25 $TgCO_{2\text{-eq}}$/yr), but not enough to offset methane emissions of 1.2 $TgCO_{2\text{-eq}}$/yr from agricultural lands, wetlands, and other lands. The projected mean annual emission of nitrous oxide was 0.18 $TgCO_{2\text{-eq}}$/yr, of which agricultural lands and grasslands/shrublands contributed about 48 percent and 38 percent, respectively.

9.4.4.6. Mean Annual Global Warming Potential of Ecosystems

Among the ecosystems in the Western United States, grasslands/shrublands were projected to play a primary role in the uptake of methane and release of nitrous-oxide with a combined mean annual flux rate of −4.0 to −3.8 $TgCO_{2\text{-eq}}$/yr for the two gases, followed by forests (−1.25 to −1.21 $TgCO_{2\text{-eq}}$/yr). Wetlands were projected to have the highest methane emissions with a mean annual rate of 1.43 to 1.75 $TgCO_{2\text{-eq}}$/yr. Grasslands/shrublands, which were projected to cover about 59 percent of the Western United States, were projected to contribute the most nitrous oxide emissions (53 percent of the total). Agricultural lands, which were projected to cover only 6 percent of the Western United States, were projected to emit 16 percent of the total nitrous oxide.

Figure 9.4 shows the projected GHG fluxes in the Western United States from 2006 to 2050, by LULC scenario. The projected carbon dioxide fluxes indicated more interannual variability than either the projected methane or nitrous oxide fluxes because the carbon dioxide projections included climate-change projections and the projected fluxes of the other two GHGs did not. The projected fluxes of methane ranged from 2.8 to 3 $TgCO_{2\text{-eq}}$/yr and diverged among the three IPCC_SRES scenarios, with an increasing trend (less than 0.004 $TgCO_{2\text{-eq}}$/yr) under the B1 scenario and slightly decreasing trends under the A1B and A2 scenarios. The projected nitrous-oxide emissions indicated minimal variability over time, with a projected mean annual flux of 1.7 $TgCO_{2\text{-eq}}$/yr in the Western United States.

Table 9.4. The projected minimum and maximum of the mean annual carbon dioxide, methane, and nitrous oxide fluxes and their total global warming potential (GWP), averaged from 2006 to 2050, by ecoregions and ecosystems.

[Projected fluxes of methane and nitrous oxide were estimated by the spreadsheet model, and projected flux of carbon dioxide was estimated from the spreadsheet model, CENTURY model, and EDCM. $TgCO_{2\text{-eq}}$, teragrams of carbon dioxide equivalent per year]

Ecoregion	Ecosystem	Area (km^2)	Carbon dioxide ($TgCO_{2\text{-eq}}$/yr)		Methane ($TgCO_{2\text{-eq}}$/yr)		Nitrous oxide ($TgCO_{2\text{-eq}}$/yr)		Global warming potential ($TgCO_{2\text{-eq}}$/yr)	
			Min	Max	Min	Max	Min	Max	Min	Max
Western Cordillera	Forests	−191.9	−25.9	−0.89	−0.88	0.3	0.31	−192.49	−26.47	−7.0
	Grasslands/shrublands	−29.1	1.2	−0.82	−0.81	0.23	0.24	−29.69	0.63	0.3
	Agricultural lands	−3.8	0.1	−0.01	−0.01	0.02	0.02	−3.79	0.11	0.0
	Wetlands	−1.5	0	0.37	0.42	0	0	−1.13	0.42	0.0
	Other lands	−0.8	0.1	0.03	0.03	0.01	0.01	−0.76	0.14	0.0
	Total	−227.2	−24.4	−1.29	−1.26	0.58	0.58	−227.91	−25.08	−6.7
Marine West Coast Forest	Forests	−29.5	6.5	−0.22	−0.2	0.03	0.03	−29.69	6.33	1.8
	Grasslands/shrublands	−1.3	0.1	−0.01	0	0	0	−1.31	0.1	0.0
	Agricultural lands	−1.8	0.7	−0.01	0	0.01	0.01	−1.8	0.71	0.2
	Wetlands	−0.4	−0.1	0.12	0.15	0	0	−0.28	0.05	0.0
	Other lands	−1.7	−0.5	0.42	0.42	0.02	0.02	−1.26	−0.06	−0.1
	Total	−34.8	6.7	0.32	0.34	0.06	0.07	−34.42	7.11	1.8
Cold Deserts	Forests	−28.4	−2.9	−0.42	−0.42	0.06	0.06	−28.76	−3.26	−0.8
	Grasslands/shrublands	−32.1	16.4	−2.8	−2.74	0.18	0.19	−34.72	13.85	4.5
	Agricultural lands	−17.4	−0.1	−0.07	−0.06	0.13	0.16	−17.34	0	0.0
	Wetlands	−1.4	0.1	0.74	0.87	0	0	−0.66	0.97	0.0
	Other lands	−0.9	0.3	0.41	0.41	0.02	0.02	−0.47	0.73	0.1
	Total	−80.2	13.8	−2.08	−1.99	0.39	0.42	−81.89	12.23	3.8
Warm Deserts	Forests	−1.9	0.1	−0.02	−0.02	0	0	−1.92	0.08	0.0
	Grasslands/shrublands	−14.4	19.7	−1.03	−1.01	0.37	0.38	−15.06	19.07	5.4
	Agricultural lands	−4.9	0	−0.01	−0.01	0.02	0.02	−4.89	0.01	0.0
	Wetlands	−0.3	0	0.07	0.07	0	0	−0.23	0.07	0.0
	Other lands	−0.4	0.2	0.05	0.05	0.02	0.02	−0.33	0.27	0.0
	Total	−21.8	20	−0.94	−0.92	0.42	0.42	−22.32	19.5	5.4
Mediterranean California	Forests	−21.3	−7.2	−0.11	−0.11	0.02	0.02	−21.39	−7.29	−2.0
	Grasslands/shrublands	−10.9	2.2	−0.16	−0.13	0.06	0.07	−11	2.14	0.6
	Agricultural lands	−18.4	0.4	0.79	0.86	0.08	0.1	−17.53	1.36	0.1
	Wetlands	−1.3	0	0.13	0.24	0	0	−1.17	0.24	0.0
	Other lands	−1.9	−0.6	0.23	0.24	0.01	0.01	−1.66	−0.35	−0.2
	Total	−53.8	−5.1	0.94	1.03	0.18	0.19	−52.68	−3.88	−1.4
Western United States (total)	Forests	−273.1	−29.3	−1.66	−1.63	0.41	0.42	−274.35	−30.51	−8.0
	Grasslands/shrublands	−87.8	39.6	−4.82	−4.7	0.84	0.88	−91.78	35.78	10.8
	Agricultural lands	−46.4	1.1	0.69	0.77	0.26	0.31	−45.45	2.18	0.3
	Wetlands	−5	0	1.43	1.75	0	0	−3.57	1.75	0.0
	Other lands	−5.6	−0.5	1.14	1.15	0.08	0.08	−4.38	0.73	−0.1
	Total	−417.9	10.9	−3.05	−2.8	1.63	1.68	−419.32	9.78	2.9

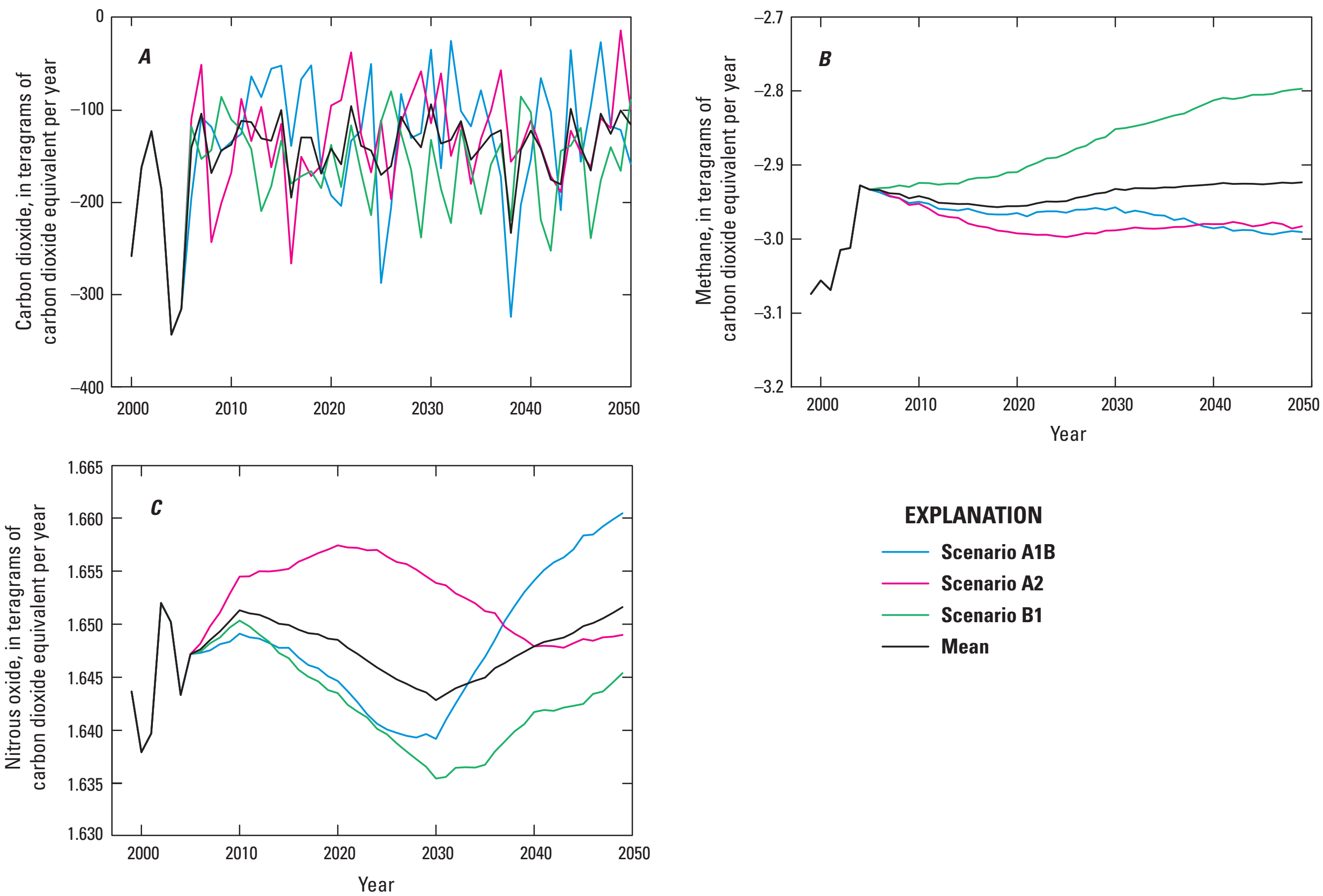

Figure 9.4. Graphs showing the baseline and projected temporal changes in global warming potential (GWP) of carbon dioxide, methane, and nitrous oxide fluxes from 2006 to 2050. *A*, Carbon dioxide. *B*, Methane, *C*, Nitrous oxide. $TgCO_{2\text{-eq}}$/yr, teragrams of carbon dioxide equivalent per year.

9.5. Summary

Using multiple biogeochemical models on the GEMS platform, projected LULC change data, and climate-change scenarios, the projected dynamics of carbon stocks, net ecosystem carbon balance, and GHG fluxes during the period from 2006 to 2050 were assessed. The results indicated that the total carbon stored in the ecoregions of the Western United States was projected to reach from 13,743 to 19,406 TgC by 2050, with the variability resulting from using different biogeochemical models, the LULC scenarios, and climate-change projections. About 80 percent of the total carbon stored would be equally allocated to the live biomass and soil organic carbon pools, and the rest would be allocated to the dead biomass pool (such as forest litter and dead, woody debris). The Western Cordillera ecoregion was projected to store the most carbon by 2050 (59 percent of the total) in the Western United States, and the Warm Deserts ecoregion was projected to store the least (4 percent). Forests were projected to have the highest carbon density with average stocks of 15.3 kgC/m^2, followed by wetlands (9.0 kgC/m^2), agricultural lands (5.4 kgC/m^2), grasslands/shrublands (2.4 kgC/m^2), and other lands (0.6 kgC/m^2).

The projected mean annual NECB varied from −113.9 to 2.9 TgC/yr as the result of the 21 simulation model runs, with approximately 50 percent of the total carbon accumulated in live biomass, 44 percent in soil organic carbon, and the remaining 5 percent in dead biomass. Compared to the baseline net carbon flux estimates for 2001 to 2005 (−162.9 to −13.6 TgC/yr, chapter 5 of this report), the projected future carbon-sequestration rates in the Western United States indicated a decline of 16.5 to 49 TgC/yr by 2050 (the end of the projection period). The Western Cordillera ecoregion was projected to be the largest carbon sink, sequestering 65 percent of the total stored carbon in the Western United States, whereas the Warm Deserts ecoregion was projected to be a small carbon source, emitting 0.2 TgC/yr. Wetlands and forests were projected to have relatively strong mean per-unit-of-area carbon-sequestration rates (−57 gC/m^2/yr and −50 gC/m^2/yr, respectively), followed by agricultural lands (−40 gC/m^2/yr), other lands (−3.9 gC/m^2/yr), and grasslands/shrublands (−3.5 gC/m^2/yr). The projected NECB and per-unit-of-area flux estimates varied spatially among ecoregions and ecosystems, and they varied temporally over the projection period, which indicated that each of the ecosystems could be a carbon sink or source for a given ecoregion, driven by LULC, climate, land management, and wildland-fire disturbance conditions.

The projected mean annual fluxes of methane and nitrous oxide were shown to be largely low to neutral, continuing the trend from the baseline period. The Western United States was projected to take up methane at a mean annual rate of −3.1 to −2.8 $TgCO_{2\text{-}eq}$/yr. The annual average nitrous oxide emission was projected to range from 1.63 to 1.68 $TgCO_{2\text{-}eq}$/yr. Given that the mean annual net flux of carbon dioxide in the Western United States was projected to range from −417.9 to 10.9 $TgCO_{2\text{-}eq}$/yr, the total combined GWP for the Western United States was projected to range from −419.3 to 9.8 $TgCO_{2\text{-}eq}$/yr. Although forests and grasslands/shrublands were projected to be a sink for methane, with an average sequestration rate ranging from −1.7 to −4.8 $TgCO_{2\text{-}eq}$/yr, the other ecosystems (agricultural lands, wetlands, and other lands) acted as a methane source, with wetlands emitting the most methane (1.6 $TgCO_{2\text{-}eq}$/yr).