Toward an Integrated Assessment of Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of the Western United States—Further Analyses and Observations

By Shuguang Liu, Zhiliang Zhu, Terry L. Sohl, Todd J. Hawbaker, Benjamin M. Sleeter, Sarah M. Stackpoole, and Richard A. Smith

Chapter 12 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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Contents

Figures

Tables

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Chapter 12. Toward an Integrated Assessment of Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of the Western United States—Further Analyses and Observations

By Shuguang Liu[1], Zhiliang Zhu[2], Terry L. Sohl[1], Todd J. Hawbaker[3], Benjamin M. Sleeter[4], Sarah M. Stackpoole[3], and Richard A. Smith[2]

12.1. Highlights

- The sum of the estimated mean net fluxes of carbon from terrestrial and aquatic pools was approximately −91.0 teragrams of carbon per year (TgC/yr) in the Western United States from 2001 to 2005. Terrestrial ecosystems sequestered 95 percent of the total carbon sequestered in the region. This rate of the total ecosystem carbon sequestration is equivalent to 4.9 percent of the total greenhouse-gas emissions from the United States in 2010.
- Compared with the baseline net ecosystem carbon balance (NECB) estimates for terrestrial ecosystems, which ranged from −162.9 to −13.6 TgC/yr, the projected future potential NECB for terrestrial ecosystems in the Western United States ranged from −113.9 to 2.9 TgC/yr, representing a potentially significant decline by as much as 30 to 121 percent (or from 16.5 to 49 TgC/yr). This projected decrease was estimated by considering land-use- and land-cover- (LULC-) change scenarios and general circulation models, incorporating simulated wildland-fire disturbances, and using biogeochemical models.
- The estimated baseline wildland-fire emissions were equivalent to 11 to 12 percent of the estimated rate of sequestration by terrestrial ecosystems in the Western United States. Because wildland-fire emissions were projected to increase and sequestration by terrestrial ecosystems was projected to decline under future climate conditions, the projected wildland-fire emissions could potentially be equivalent to 27 to 43 percent of the projected sequestration by terrestrial ecosystems. The carbon stored in arid and semiarid regions of the Western United States was especially vulnerable to wildland-fire emissions under both the baseline and projected future conditions.

12.2. Introduction

This assessment was a multidisciplinary effort to study carbon stocks, carbon sequestration, and greenhouse-gas (GHG) fluxes in terrestrial and aquatic ecosystems in the context of major controlling processes such as land-use and land-cover (LULC) changes, climate changes, and wildland-fire occurrences. All of the major ecosystems were included in the assessment in a spatially and temporally explicit fashion, thus allowing for opportunities to analyze relations between input and output data, parameters and estimates, drivers and results, and geographies and time horizons. Specifically, there are four objectives for this chapter:

1. Examine the baseline carbon stocks, sequestration, and fluxes that were estimated from the different assessment components (chapters 2, 3, 5, 10, and 11) in order to provide a heuristic view of the carbon cycle and budget in the Western United States.
2. Compare similarities and differences between the estimated baseline and projected terrestrial net carbon fluxes and greenhouse-gas (GHG) fluxes. Because projections were not available for inland aquatic ecosystems, the comparison does not include processes related to them.
3. Synoptically examine the impacts of LULC change, disturbances, and climate change on carbon stocks and sequestration across the Western United States.
4. Discuss and summarize the major accomplishments and limitations of this assessment.

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12.3. Observations and Examinations

12.3.1. Carbon Cycle and Budget in Terrestrial and Aquatic Systems During the Baseline Period

The estimated baseline (2001–2005) carbon stocks and changes in carbon stocks (fluxes) of the pools that were studied in the Western United States and were calculated during this assessment are shown in figure 12.1. The diagram depicts the results from the previous chapters. For simplicity, the estimated carbon stocks in all terrestrial ecosystems were lumped together in this diagram within two carbon pools: one for biomass carbon and the other for soil organic carbon (chapter 5 of this report). The emissions from wildland-fire combustions represented average conditions between 2001 and 2008 (chapter 3 of this report). Aquatic fluxes and sequestration (chapters 10 and 11) were based on input data representing average conditions from the 1970s to 2012.

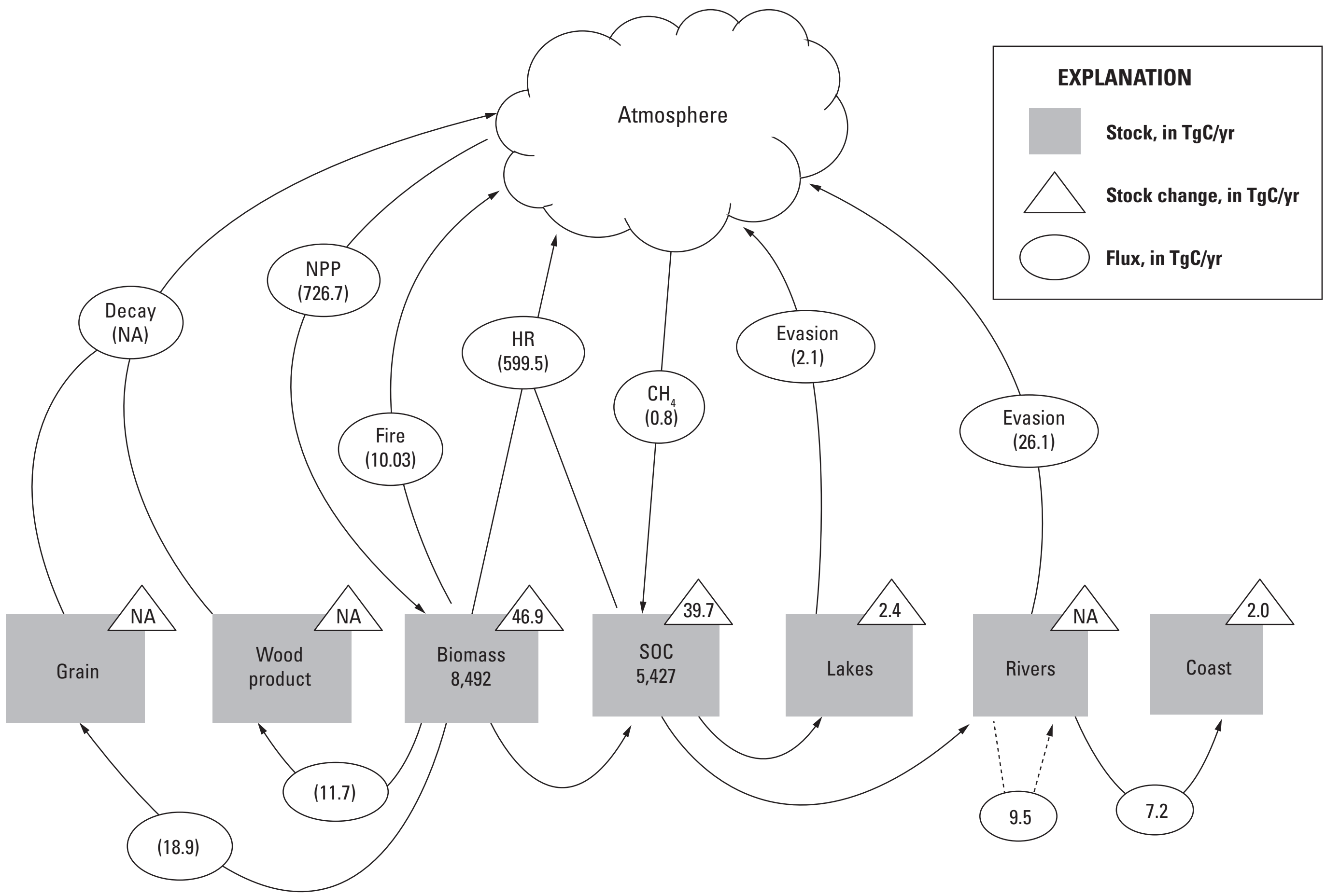

Figure 12.1. Flow diagram showing average carbon stocks and fluxes and changes in average carbon stock for primary carbon pools in the Western United States during the baseline period (2001–2005). Not all carbon stocks and fluxes are included in this diagram; only those stocks and fluxes that were examined in the assessment are shown. Changes in carbon storage rates in lacustrine systems (lakes and reservoirs) and in coastal waters (by burial in sediment) were included, but the carbon stocks in these ecosystems were not included. In quantifying the changes in average carbon stocks of soils and biomass, carbon combustion by fire and transfer to products by harvesting were considered but not their export to the aquatic ecosystems. There was no coupling between the estimates of carbon stocks in the terrestrial and aquatic systems. Positive carbon stock change indicates a carbon storage increase, and therefore represents carbon sequestration. The dotted arrow under the "Rivers" box indicates the lateral flux of carbon within the streams and rivers. NA, not applicable, due to either a lack of input data or the choice of methods; NPP, net primary production of terrestrial ecosystems; HR, heterotrophic respiration of terrestrial ecosystems; SOC, soil organic carbon; TgC/yr, teragrams of carbon per year.

As noted in chapter 1 of this report and above, the baseline years varied for different components of the overall carbon cycle because of the varying availability of input data. As a result, figure 12.1 should be interpreted as a composite representation of contemporary carbon-cycle processes in the region. The common time period for all the components was from 2001 to 2005, which is the nominal baseline period for this assessment (chapter 1 of this report).

On average, the terrestrial ecosystems (forests, agricultural lands, grasslands/shrublands, wetlands, and other lands) in the five ecoregions of the Western United States stored a total of 13,919 TgC during the baseline period (2001–2005). Carbon in biomass pools (such as live and dead vegetative materials aboveground and belowground, except for those removed from agricultural fields and forests) accounted for 8,492 TgC (61 percent) of the total, and the rest was stored in the top 20 cm of the soil layer. Carbon stored in other pools (such as grain and wood products removed from the landscape) was not estimated in this assessment, although its influx was calculated. The regional NECB was estimated to be −91.0 TgC/yr in the Western United States. This estimate represented the sum of carbon removed from the atmosphere and sequestered in terrestrial pools and in sediments in lakes, reservoirs, and coastal waters in this region. Of the total NECB in the region, the terrestrial ecosystems were responsible for an average of −86.6 TgC/yr (95 percent of the total NECB), including −46.9 TgC/yr and −39.7 TgC/yr in biomass and soils, respectively (fig. 12.1). The average amount of carbon sequestered annually in the Western United States during the baseline period was equivalent to about 4.9 percent of the fossil-fuel emissions in the United States in 2010 (EPA, 2012).

Among the various types of flux, the largest were the net primary production (NPP) and heterotrophic respiration of the terrestrial ecosystems. About 12 percent of the annual NPP was sequestered in biomass and soils. The amount of carbon removed by timber harvesting (only clearcut areas were considered) from the landscape was 11.7 TgC/yr, which was similar in magnitude to the carbon emissions from wildland fires (10.0 TgC/yr). The amount of carbon removed by harvesting grain from agricultural lands was 18.9 TgC/yr, which is a large amount considering that agricultural land was not the dominant land-cover type in the Western United States. The amount of carbon removed by timber harvesting was largely underestimated compared with estimates in other studies (Hudiburg and others, 2011; D.P. Turner, Ritts, and others, 2011) and in the U.S. Department of Agriculture's timber statistics reports (USDA, 2011a). The underestimation was likely caused by the omission of partial forest cutting in the assessment, which was due to the absence of geospatial data layers describing the location, extent, and intensity of partial forest cutting with adequate spatial and temporal resolution.

Although carbon fluxes related to timber and grain harvesting were estimated, no life-cycle analysis was conducted to evaluate the long-term decomposition rates of the harvests. Also not included in this assessment were carbon fluxes related to forest thinning, forest defoliation and mortality from insects, and rangeland grazing. As documented in chapter 4 of this report, these land-management concerns and natural disturbances, which are highly relevant to the carbon cycle in the Western United States, were not supported with sufficient input data. As a result, their exclusion introduced uncertainty in the assessment.

Inland aquatic ecosystems in the Western United States represented only a small portion of the total area (1.5 percent), but they played an important role in determining the fate of a large portion of the total carbon flux in the region. The total flux (lateral and efflux) of inland aquatic ecosystems at 37.7 TgC/yr was previously unaccounted for and is regionally significant (such as in the Marine West Coast Forest ecoregion). Several processes related to the carbon cycle of the inland and coastal aquatic systems were not included in the study: the effluxes of carbon dioxide from the Pacific coastal waters, lateral transport of carbon by soil erosion and deposition, and the interactions of carbon between terrestrial and aquatic ecosystems.

The export of carbon by riverine systems into the Pacific coastal waters was estimated to be 7.2 TgC/yr. Only a small amount of the carbon exported by riverine system was estimated to be stored in the Pacific coastal waters, but terrestrial processes (such as primary production by different terrestrial ecosystems) were directly involved in storing approximately 2.0 TgC/yr.

12.3.2. Comparing Baseline and Projected Future Estimates of Net Ecosystem Carbon Balance

The minimum and maximum estimates of the mean terrestrial net ecosystem carbon balance are listed in table 12.1 for both baseline (2001–2005) and projected future (2006–2050) conditions. The negative NECB values indicate carbon sequestration in terrestrial ecosystems, and positive values suggest carbon loss from ecosystems (partially by lateral transport of terrestrial ecosystems, such as grain and timber harvesting).

Table 12.1. Minimum and maximum estimates of mean net ecosystem carbon balance under baseline (2001–2005) and projected future (2006–2050) conditions for all major ecosystems for the Western United States.

[Negative net ecosystem carbon balance (NECB) values indicate carbon sequestration in terrestrial ecosystems and positive values indicate carbon loss. Minimum mean and maximum mean represent the annual means of the minimum and maximum NECB among the 21 General Ensemble Modeling System (GEMS) simulations over the baseline and projection periods under various biogeochemical models, land-use- and land-cover-change scenarios, and climates projected by general circulation models (see chapters 5 and 9 of this report). For the column indicating the difference between the baseline and projected NECB, negative values indicate a decrease in NECB from baseline to future projections, and positive values indicate an increase. TgC/yr, teragrams of carbon per year]

Ecoregion	Ecosystem	Baseline NECB (TgC/yr)		Projected NECB (TgC/yr)		Difference between baseline and projected NECB (TgC/yr)	
		Minimum mean	Maximum mean	Minimum mean	Maximum mean	Minimum mean	Maximum mean
Western Cordillera	Forests	−70.3	−19.6	−52.3	−7.0	−18.0	−12.6
	Grasslands/shrublands	−14.6	0.2	−7.9	0.3	−6.7	−0.1
	Agricultural lands	−0.4	0.0	−1.0	0.0	0.6	0.0
	Wetlands	−0.7	−0.1	−0.4	0.0	−0.3	−0.1
	Other lands	−0.2	0.4	−0.2	0.0	0.0	0.4
	Total	−86.2	−19.1	−61.8	−6.7	−24.4	−12.4
Marine West Coast Forest	Forests	−6.0	−1.3	−8.1	1.8	2.1	−3.1
	Grasslands/shrublands	−0.7	0.0	−0.4	0.0	−0.3	0.0
	Agricultural lands	0.0	0.1	−0.5	0.2	0.5	−0.1
	Wetlands	0.0	0.0	−0.1	0.0	0.1	0.0
	Other lands	−0.2	0.2	−0.5	−0.1	0.3	0.3
	Total	−6.9	−1.0	−9.6	1.9	2.7	−2.9
Cold Deserts	Forests	−7.8	1.5	−7.7	−0.8	−0.1	2.3
	Grasslands/shrublands	−20.9	3.8	−8.7	4.5	−12.2	−0.7
	Agricultural lands	−3.0	0.0	−4.7	0.0	1.7	0.0
	Wetlands	−0.6	0.0	−0.4	0.0	−0.2	0.0
	Other lands	−0.3	0.4	−0.2	0.1	−0.1	0.3
	Total	−32.6	5.7	−21.7	3.8	−10.9	1.9
Warm Deserts	Forests	−0.6	0.2	−0.5	0.0	−0.1	0.2
	Grasslands/shrublands	−16.1	2.7	−3.9	5.4	−12.2	−2.7
	Agricultural lands	−1.8	0.0	−1.3	0.0	−0.5	0.0
	Wetlands	0.0	0.0	−0.1	0.0	0.1	0.0
	Other lands	−0.1	0.0	−0.1	0.0	0.0	0.0
	Total	−18.6	2.9	−5.9	5.4	−12.7	−2.5
Mediterranean California	Forests	−6.1	−2.6	−5.8	−2.0	−0.3	−0.6
	Grasslands/shrublands	−6.4	0.3	−3.0	0.6	−3.4	−0.3
	Agricultural lands	−5.6	0.2	−5.0	0.1	−0.6	0.1
	Wetlands	−0.1	0.1	−0.3	0.0	0.2	0.1
	Other lands	−0.4	−0.1	−0.5	−0.2	0.1	0.1
	Total	−18.6	−2.1	−14.6	−1.5	−4.0	−0.6
Western United States (total)	Forests	−90.8	−21.8	−74.4	−8.0	−16.4	−13.8
	Grasslands/shrublands	−58.7	7.0	−23.9	10.8	−34.8	−3.8
	Agricultural lands	−10.8	0.3	−12.5	0.3	1.7	0.0
	Wetlands	−1.4	0.0	−1.3	0.0	−0.1	0.0
	Other lands	−1.2	0.9	−1.5	−0.2	0.3	1.1
	Total	−162.9	−13.6	−113.6	2.9	−49.3	−16.5

During the baseline period, the NECB of the terrestrial ecosystems in the Western United States was estimated to range from −162.9 to −13.6 TgC/yr, with a mean value of −86.6 TgC/yr. In comparison, the projected future range of the NECB was estimated to range from −113.6 to 2.9 TgC/yr. The comparison in table 12.1 indicates a projected decline in future potential sequestration ranging from 16.5 to 49.3 TgC/yr, which represents an estimated 30 to 121 percent decrease in the potential of those ecosystems to sequester carbon.

The projected decline in the NECB was highly variable among ecoregions and ecosystems. Forests were estimated to be the largest carbon sink during the baseline period with a mean rate of −53.9 TgC/yr, which accounted for 62 percent of the total NECB in the Western United States; however, this sink was projected to decrease by 13.8 to 16.4 TgC/yr by 2050. This result correlates with previous studies which hypothesized that the aging of forest ecosystems in the United States may result in weakened carbon sequestration by forests over time (Hurtt and others, 2002; Pan, Chen, and others, 2011; D.P. Turner, Ritts, and others, 2011). Grasslands/shrublands were estimated to be the second largest carbon sink during the baseline period because of their extensive coverage of part of the Western United States; however, this estimated sink was projected to have the largest decrease in the NECB, with losses ranging from 34.8 to 3.8 TgC/yr by 2050. In general, the NECB in the rest of the ecosystems in the Western United States was projected to remain relatively stable between the baseline and projected time periods.

Table 12.2 shows the differences between the baseline estimated mean annual NECB (table 5.4 of chapter 5) and the projected mean annual NECB by biogeochemical model, climate-change scenario, and general circulation model (table 9.2 of chapter 9) for each ecoregion and for the Western United States as a whole. Among the three biogeochemical models, the CENTURY model projected the largest decrease for the Western United States as a whole, followed by the spreadsheet model and the Erosion-Deposition-Carbon Model (EDCM). The EDCM projected an increase in the NECB in the Cold and Warm Deserts ecoregions, whereas the CENTURY model projected a decrease of about 20 percent and the spreadsheet model projected a similar trend. All three biogeochemical models projected that the NECB for the Marine West Coast Forest would remain relatively flat.

Table 12.2. Differences between the baseline and projected net ecosystem carbon balance for each ecoregion, categorized by biogeochemical model, land-use- and land-cover-change scenario, and general circulation model.

[CCCma CGCM3.1, Canadian Centre for Climate Modelling and Analysis's Coupled Global Climate Model version 3.1; CSIRO-Mk3.0, Commonwealth Scientific and Industrial Research Organization Mark 3.0; EDCM, Erosion-Deposition-Carbon Model; GCM, general circulation model; MIROC 3.2-medres, Model for Interdisciplinary Research on Climate (version 3.2, medium resolution); TgC/yr, teragrams of carbon per year]

Model or scenario	Western Cordillera (TgC/yr)	Marine West Coast Forest (TgC/yr)	Cold Deserts (TgC/yr)	Warm Deserts (TgC/yr)	Mediterranean California (TgC/yr)	Western United States (TgC/yr)
CENTURY biogeochemical model	−31.2	−0.2	−22.4	−18.7	−5.3	−77.7
EDCM biogeochemical model	−5.7	−0.3	7.3	2.3	−6.0	−2.4
Spreadsheet biogeochemical model	−10.0	−1.7	−0.4	−0.1	−0.5	−12.7
A1B scenario	−19.3	−1.6	−6.6	−7.2	−5.1	−39.8
A2 scenario	−17.6	−1.3	−6.8	−7.2	−4.8	−37.6
B1 scenario	−14.8	1.6	−6.3	−6.7	−4.7	−30.9
CCCma CGCM3.1 GCM	−18.2	−0.1	−7.8	−8.7	−5.6	−40.3
CSIRO–Mk3.0 GCM	−18.1	−0.4	−4.3	−6.0	−5.5	−34.4
MIROC 3.2–medres GCM	−19.0	−0.2	−10.5	−9.9	−5.8	−45.3

The differences between the baseline and projected carbon fluxes under the three scenarios chosen from the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (IPCC–SRES; Nakicenovic and others, 2000) were relatively consistent, varying from −39.8 TgC/yr (A1B scenario) to −30.9 TgC/yr (B1 scenario) for the entire Western United States, and this consistency can also be seen across all the ecoregions. The climate projections affected the magnitude of carbon-flux change as well. The most significant decline of −45.3 TgC/yr was projected under the Model for Interdisciplinary Research on Climate (version 3.2, medium resolution; MIROC 3.2-medres), and the smallest decline (−34.4 TgC/yr) was projected under the Commonwealth Scientific and Industrial Research Organization Mark 3.0 (CSIRO–Mk3.0) model. The largest differences in carbon flux under the different GCMs were manifested in the Cold and Warm Deserts, which were the most climate-sensitive ecoregions in the Western United States.

12.3.3. Preliminary Observations of Land-Use and Land-Cover Change, Disturbances, and Climate Change

12.3.3.1. Land-Use and Land-Cover Change

The effects of estimated LULC change on carbon sequestration were observed by examining the net change in area and the net change in the amount of carbon stored (NECB) within three major ecosystems in the Western United States (forests, grasslands/shrublands, and agricultural lands). Each 5-year time period was plotted for each of the three scenarios (fig. 12.2). Although figure 12.2 may be useful for examining some effects of LULC change, interpretations should be made with these caveats:

- The changes in carbon storage depicted in figure 12.2 were all-inclusive and represented not only the effects of net LULC change, but also the effects of other driving forces such as climate change and location-specific LULC transitions.
- Gross LULC change (LULC transitions both to and from a given LULC class) may have led to a change in carbon storage, even if there was no net change in area, because of the geographic differences in carbon storage within the same land cover. The effects of gross LULC change on carbon could be investigated in the future.
- Changes in carbon storage in each LULC category did not necessarily indicate carbon sequestration from or release to the atmosphere. The changes may have simply indicated the reassignment of carbon storage from one LULC type to another following a LULC transition. For example, if an area of marginal agricultural land (with an assumed amount of carbon storage of 3,000 gC/m^2) transitions to grassland (with an assumed amount of carbon storage of 3,030 gC/m^2), it could incur a net carbon gain of 30 gC/m^2/yr. The change in carbon storage would be indicated as a loss of 3,000 gC/m^2 for the agricultural land and a gain of 3,030 gC/m^2 for the grassland one year after the transition.

Among the three scenarios, the rate of carbon sequestration was projected to decline precipitously over time under the A1B and A2 scenarios, while remaining relatively stable under the B1 scenario after an initial drop (fig. 12.2). An exploration of the exact causes and their relative contributions to the trends was not conducted for this report; however, the following observations were made:

- Despite either positive or negative changes in individual ecosystems, carbon storage in all ecosystems increased consistently in the Western United States throughout the projected time period, but the rate of increase declined under the A1B and A2 scenario (fig. 12.2). This result suggested a complex relation between LULC change and the net change in carbon storage that likely involved the effects of other factors. For example, the large amount of carbon sequestered in some forests may have been dictated by their relatively young age (Pan, Chen, and others, 2011), which was the result of forest-management policies that were created in the first half of the 20th century (Houghton and others, 1999; D.P. Turner, Ritts, and others, 2011). As the forests matured and aged, their sequestration capacity may have been in an overall decline.
- The projected increase in carbon storage in agricultural lands may have been largely driven by the modeled increase in biomass production capacity over time on the basis of assumptions made in the model about improvements in genetic engineering, cultivation, and management practices (S. Liu and others, 2003). On the other hand, changes in carbon storage and sequestration by grasslands/shrublands were projected to follow changes in the ecosystem's land area with a time lag.

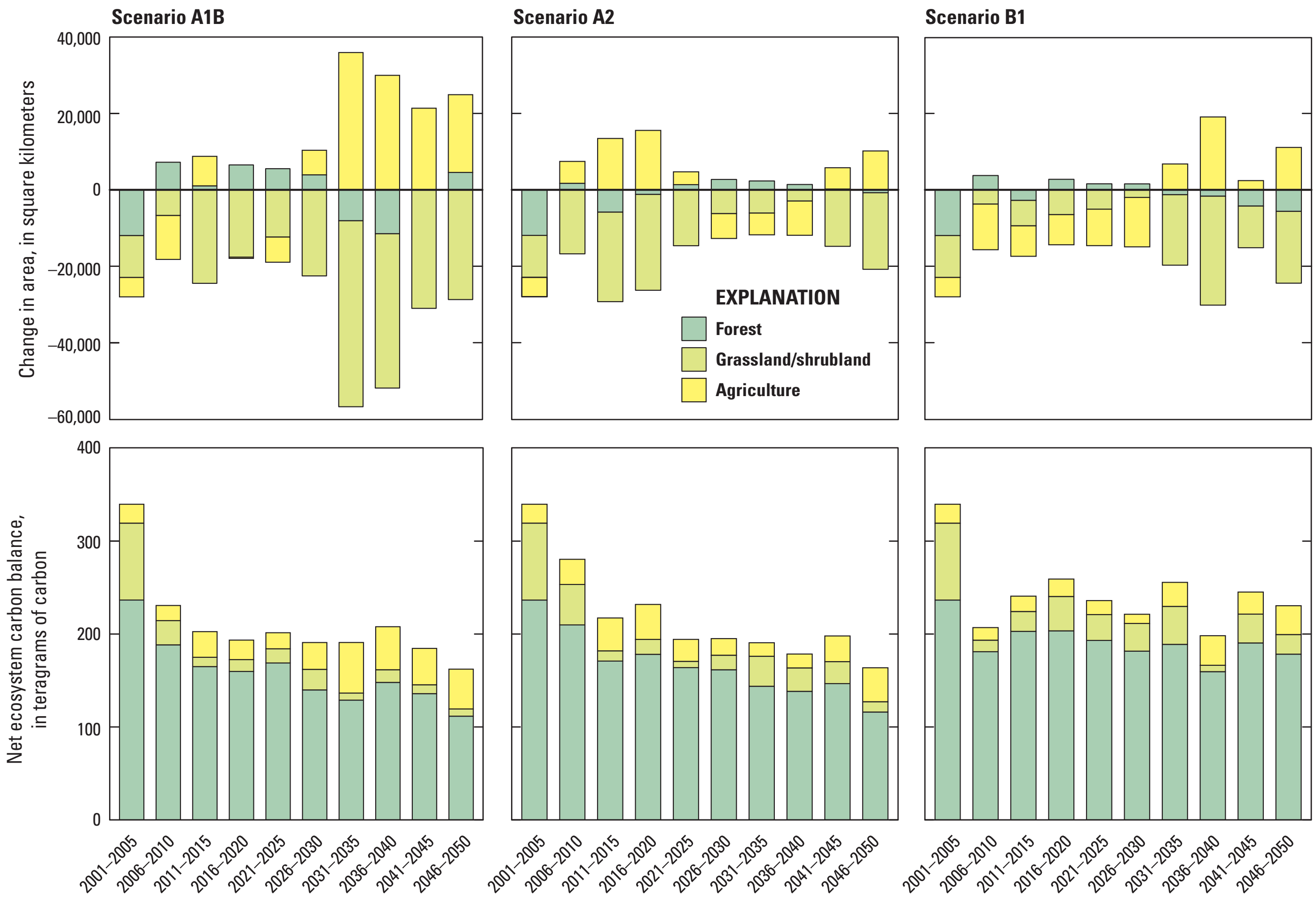

Figure 12.2. Charts showing comparisons of net change in the area of major land-use and land-cover classes and net ecosystem carbon balance (NECB), by 5-year intervals in the Western United States from the baseline (2001–2005) through the projected (2006–2050) time periods.

12.3.3.2. Land Management and Disturbances

Across the Western United States, forest cutting was projected to increase from the baseline under the A1B and A2 scenarios, but was projected to decline from the baseline under the B1 scenario (chapter 6 of this report). These projections were used to simulate the amount of timber harvested (fig. 12.3). The projections of reduced forest cutting under the B1 scenario, which effectively increased the rotation length of harvesting, largely explained the differences in carbon sequestration between the B1 scenario and the other two IPCC–SRES scenarios (fig. 12.3). For example, under the B1 scenario, the projected increase in carbon by forests was more pronounced and sustained than under the other scenarios in the Marine West Coast Forest and Western Cordillera ecoregions, where most forest cutting was expected to take place. The annual differences in carbon sequestration by forest cutting among all three IPCC scenarios were as great as 3 TgC/yr in the Marine West Coast Forest and 7.5 TgC/yr in the Western Cordillera. The results agreed well with past observations that changes in forest harvesting regimes have a large effect on carbon sequestration (Cohen and others, 1996; Houghton and others, 1999; D.P. Turner, Ritts, and others, 2011).

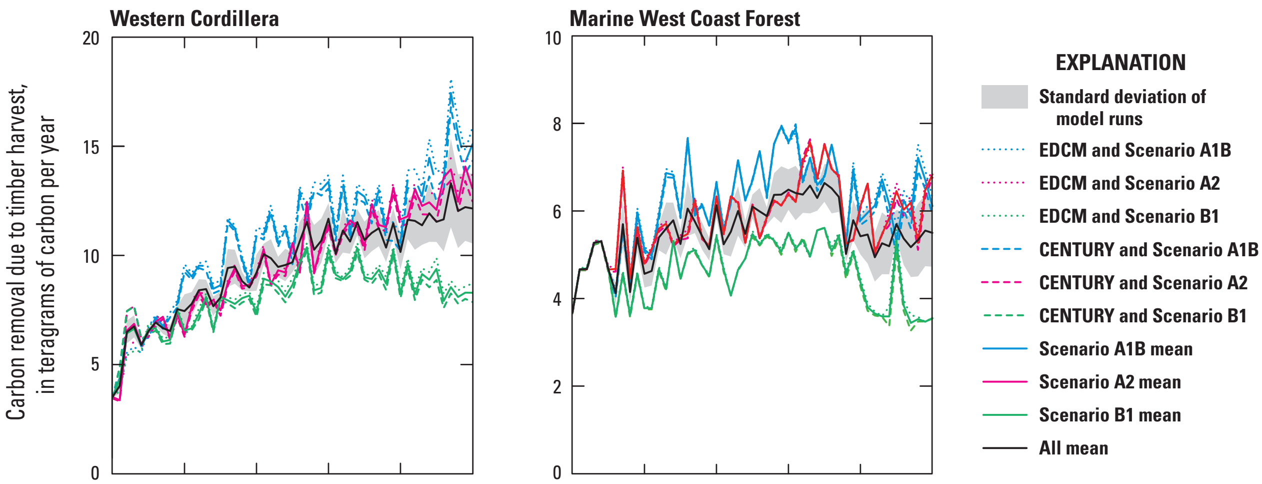

Figure 12.3. Graphs showing carbon removal from the Western Cordillera and Marine West Coast Forest ecoregions during the baseline (2001–2005) and projected (2006–2050) time periods as the result of forest harvesting activities, simulated under the three selected climate-change scenarios and two of the biogeochemical models. The other ecoregions studied in the assessment were estimated to have smaller amounts of carbon removal because they had limited forest coverage; the results from those ecoregions are not presented here. Scenarios are from the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (Nakicenovic and others, 2000). EDCM, Erosion-Deposition-Carbon Model; TgC/yr, teragrams of carbon per year.

Across the Western United States, the median area burned annually by wildland fires was 12,136 km^2 during the baseline time period (2001–2008), but the interannual variability in burned area was large; specifically, 23,261 km^2 burned during extreme years, defined as the 95th percentile of the area burned annually. Wildland fires emitted a median of 41.0 $TgCO_{2\text{-eq}}$/yr and emitted 65.0 $TgCO_{2\text{-eq}}$/yr in extreme years. Median and extreme wildfire emissions were approximately 0.07 percent and 0.13 percent, respectively, of the total carbon stock (14,182 TgC) in the Western United States from 2001 to 2008.

Both the area burned by wildland fires and GHG emissions were projected to increase in the Western United States under all three of the climate-change scenarios considered in this assessment (chapter 8 of this report). The projected median of the area burned annually increased 31 to 66 percent relative to the baseline conditions (average of 2001 to 2008, which was 12,136 km^2) and the projected median annual emissions increased 28 to 56 percent from a baseline median of 41.0 $TgCO_{2\text{-eq}}$/yr. These increases resulted in the median of the area burned annually ranging between 15,900 and 20,100 km^2 and emissions ranging between 52.5 and 64.0 $TgCO_{2\text{-eq}}$ in the decade between 2041 and 2050. Thus, a typical (median) fire year in the future could be rather similar to an extreme (95th percentile) fire year in the baseline period. Extreme fire years were projected to become even more extreme; the 95th percentile of the area burned annually increased 79 to 95 percent from baseline conditions (2001–2008), from 23,261 km^2/yr to between 41,600 and 45,400 km^2/yr. The emissions in extreme fire years increased 73 to 150 percent to between 112 and 163 $TgCO_{2\text{-eq}}$/yr relative to the 65.0 $TgCO_{2\text{-eq}}$/yr during the baseline period.

The relative amount of carbon stocks lost in each ecosystem for each year through wildland-fire emissions was projected to increase. The future potential carbon stocks in the decade between 2041 and 2050 were projected to be 16,492 TgC across the Western United States. Carbon losses through emissions in a typical fire year in the same decade were projected to range between 0.08 and 0.09 percent of the potential carbon stock, which is a 0.01 to 0.02 percent increase from the baseline time period; in an extreme fire year during the same decade, carbon losses were projected to range between 0.19 and 0.27 percent of the potential carbon stock (table 12.3). The patterns of change in carbon stocks across the Western United States were generally consistent within the ecoregions, except for the Marine West Coast Forest, where little change in wildland-fire occurrences and emissions was projected, and in Cold Deserts, where the projected changes in emissions relative to carbon stocks were small. Over the same time period, the rate of carbon sequestration was projected to decrease by 45 to 58 percent across the Western United States. Even though carbon stocks were projected to increase over time, carbon sequestration rates were projected to ultimately decrease, partially because of the projected increase in wildland-fire emissions.

Table 12.3. Estimated wildland-fire emissions relative to total ecosystem carbon stocks during typical and extreme fire years for the baseline (2001–2008) and future (2041–2050) time periods.

Ecoregion	Typical fire years (in percent)			Extreme fire years (in percent)		
	Baseline	Future projected low	Future projected high	Baseline	Future projected low	Future projected high
Western Cordillera	0.100	0.090	0.130	0.180	0.200	0.440
Marine West Coast Forest	0.010	0.010	0.010	0.010	0.000	0.010
Cold Deserts	0.040	0.050	0.070	0.070	0.120	0.150
Warm Deserts	0.090	0.100	0.160	0.230	0.200	0.460
Mediterranean California	0.060	0.050	0.070	0.110	0.110	0.120
Western United States	0.070	0.080	0.090	0.130	0.190	0.270

12.3.3.3. Effects of Climate Change

Globally, increased carbon dioxide and climate change may cause change in the terrestrial ecosystem carbon cycle (Birdsey and others, 1993). Levy and others (2004) noted that the global carbon sink for 1990 through 2100 may range between 2 and 6 PgC/yr because of different fossil-fuel-emissions scenarios (Levy and others, 2004). According to Fung and others (2005), the terrestrial carbon sink may decrease globally in the coming decades and the amount could vary, depending on emissions scenarios. In the United States, the carbon sink could continue but could weaken over the 21st century (Hurtt and others, 2002). The following observations were made on the potential effects of climate change:

- The grasslands/shrublands ecosystem in the Western United States was sensitive to climate change and variability. The temporal variability of carbon stock change (sources or sinks) in the Cold Deserts and Warm Deserts ecoregions, as examples, were high and did not follow the corresponding temporal variability of the change in the extent of the grasslands/shrublands ecosystem (fig. 12.2). Flux-tower observations at the site-specific and regional scales have shown strong interannual variability in carbon-storage changes in the grasslands/shrublands ecosystem in this region (Scott and others, 2011; Xiao and others, 2011).
- All of the GCMs consistently projected future warming trends in all ecoregions, but the degree of warming varied by GCM and ecoregion (chapter 7 of this report). The projected changes in precipitation were highly variable. Figure 12.4 compares the density functions of relative change of precipitation during two time periods: 2001 to 2010 and 2041 to 2050. All of the GCMs projected extensive changes at the pixel level as indicated by the spread and shift of the density functions from $x=0$ (which indicates no change). As an example, in the Cold Deserts ecoregion, where the carbon balance in the grasslands/shrublands ecosystem changed from a sink to a source under the A1B and A2 IPCC–SRES scenarios, two out of three GCMs suggested a 5 to 20 percent decrease in precipitation under all three IPCC–SRES scenarios (fig. 12.4).
- The GCMs projected a high degree of spatial variability in climate change even within ecoregions, as indicated by the spreading of the density curves of temperature and precipitation changes. In order to understand the effects of climate change at the ecoregion level, the spatial variability of climate change needed to be considered. For example, for the Marine West Coast Forest ecoregion, all of the GCMs projected, on average, small increases in precipitation under the A1B and A2 scenarios and small decreases under the B1 scenario; however, the patterns of carbon-storage change across scenarios in forests did not correlate to projected precipitation increases or decreases in the ecoregion. Future efforts to analyze the effects of climate may be aided by considering the spatial variability of those effects.

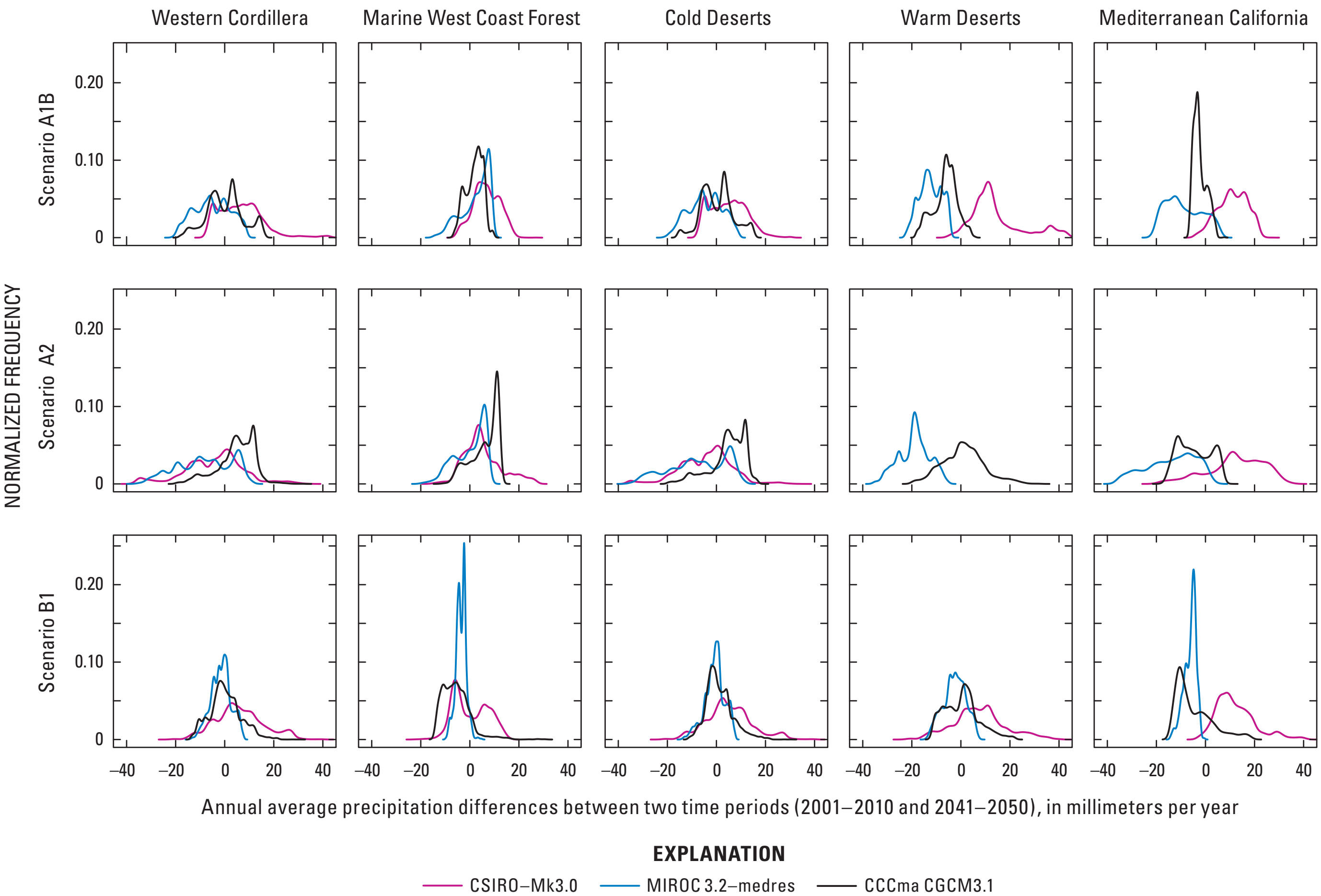

Figure 12.4. Graphs showing the distribution of annual average precipitation differences between the two time periods: 2001 to 2010 and 2041 to 2050. These averages were derived from the three general circulation models (CCCma CGCM3.1, CSIRO–Mk3.0, MIROC 3.2 medres) under three IPCC–SRES scenarios (A1B, A2, B1) for five ecoregions in the Western United States. The vertical axis shows the relative frequency and the integral (or area under each curve) equals 1. CCCma CGCM3.1, Canadian Centre for Climate Modelling and Analysis's Coupled Global Climate Model version 3.1; CSIRO–Mk3.0, Commonwealth Scientific and Industrial Research Organisation Mark 3.0 model; IPCC–SRES, Intergovernmental Panel of Climate Change's Special Report on Emissions Scenarios (Nakicenovic and others, 2000); MIROC 3.2–medres, Model for Interdisciplinary Research on Climate version 3.2, medium resolution.

12.4. Gaps, Uncertainties, and Limitations

This report covered broad and comprehensive topics designed to fulfill the requirements of the Energy Independence and Security Act of 2007 (described in chapter 1 of this report; U.S. Congress, 2007). The results, data products, and publications (including this report) were designed to assist the scientific community, land managers, and policy stakeholders in a variety of applications. Gaps in the assessment remain, however. There were both natural and anthropogenic ecosystem processes that were not explored and critical relations and feedback loops not yet analyzed and reported. The following gaps contributed to uncertainties in the results of this assessment and could be considered for future investigations.

- Major land-management activities in the Western United States (see chapter 4 of this report for more information) were not fully addressed. Two of the most important land-management activities in the Western United States, forest thinning and rangeland grazing, were not included in the assessment and their effects on carbon and GHG fluxes were not analyzed.
- Although emissions from wildland-fire combustions and effects on carbon dynamics over time were estimated using the best available data and models, an analysis of the long-term effects on net ecosystem production, including decomposition and regeneration of forests, was not included in the report.
- The estimated mean baseline carbon stock of 13,921 TgC (ranging from 12,418 to 15,460 TgC) for the Western United States reflected only terrestrial ecosystems. Baseline and projected estimates of carbon stocks were not made for the aquatic ecosystems. The estimates for the aquatic ecosystems focused only on carbon fluxes.
- Carbon sequestration estimates for both the baseline and the projected time periods were based on three future scenarios, which reflected the combined effects of LULC change, available land-management activities, wildland fires, and climate change (for future projections only). An understanding of the specific contributions by each of these controlling processes would require model runs using experimental designs. Instead, for this report, only preliminary analyses of possible individual effects were provided.

For all of the major technical processes in this assessment, practical efforts were made to validate baseline estimates and evaluate uncertainties in both the baseline and projected results. The validation steps and uncertainty in the results have been documented in this report. Uncertainties were quantified based on traditional statistical methods to account for the spread of multiple model runs. The actual spread of uncertainties in the results, as well as contributions from specific sources (including input data, model structure and parameterization, shortfalls in land-management activities and natural disturbances (as noted above), and connections or coupling between technical components of the assessment methodology) were not statistically quantified. Additional observations concerning uncertainties were made:

- The LULC changes and wildland-fire disturbances were modeled and estimates were made separately. The estimates were calculated for each pixel, but these estimates were not integrated; therefore, it is possible that a forest pixel that was modeled to be burned would still have a chance of being harvested at the same time or within a few years of the wildland-fire occurrence. Nevertheless, over the scale of an ecoregion, the integration of LULC with wildland-fire models and estimates is unlikely to be a major source of uncertainty.
- Aquatic and terrestrial methods were not coupled such that the aquatic methods used direct input from terrestrial models (for example, erosion and deposition) in order to estimate the effects and fate of terrestrial exports. Thus, it is uncertain how much of the aquatic carbon fluxes came from terrestrial sources. In addition, the possibility of overlaps in counting the surface areas between aquatic features (such as streams and rivers) and terrestrial ecosystems (such as wetlands) could lead a small portion of carbon fluxes to be counted twice.
- Ultimately, for projected future potential carbon storage and fluxes, it is the use of various input data layers (including the LULC-change and climate-change scenarios within the three IPCC–SRES storylines) and biogeochemical models that dictated the overall spread of the uncertainties in the assessment results. Uncertainties from these models and data layers were undoubtedly large, and future effort should emphasize the quantification and attribution of uncertainty in estimating carbon sequestration over large areas.

In using this report, as well as publications and data products generated for the assessment, caution should be exercised by considering the above-noted constraints and uncertainties together with the major findings and unique aspects of the assessment. In addition, this assessment was conducted in the framework of the five ecoregions, which were used to parameterize the assessment models. The results were therefore presented at the ecoregional scale. Therefore, although this assessment's spatial-data products were delivered at a 250-m-pixel resolution, the scale of the ecoregions is the most appropriate scale for applying the results of this assessment to further activities.

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