Baseline Carbon Storage, Carbon Sequestration, and Greenhouse-Gas Fluxes in Terrestrial Ecosystems of the Western United States

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

Chapter 5 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 5. Baseline Carbon Storage, Carbon Sequestration, and Greenhouse-Gas Fluxes in Terrestrial Ecosystems of the Western United States

By Shuguang Liu[1], Jinxun Liu[2], Claudia J. Young[3], Jeremy M. Werner[1], Yiping Wu[4], Zhengpeng Li[5], Devendra Dahal[2], Jennifer Oeding[2], Gail L. Schmidt[2], Terry L. Sohl[1], Todd J. Hawbaker[6], and Benjamin M. Sleeter[7]

5.1. Highlights

- From 2001 to 2005 in the Western United States, the average annual total carbon stored in vegetation and soils (up to 20 cm in depth) was estimated to be 13,920 TgC, ranging from 12,418 to 15,461 TgC.
    - The Western Cordillera ecoregion stored the most carbon (59 percent of the total), followed by the Cold Deserts (19 percent), Marine West Coast Forest (11 percent), Mediterranean California (6 percent), and Warm Deserts (5 percent) ecoregions.
    - Forests, grasslands/shrublands, and agricultural lands stored 69 percent, 25 percent, and 4.3 percent of the total carbon in ecosystems of the Western United States, respectively.
    - Live biomass, soil organic carbon (SOC) in the top 20 cm of the soil layer, and dead biomass (forest litter and dead woody debris) accounted for 38 percent, 39 percent, and 23 percent, respectively, of the total carbon stored in the Western United States.
- The average annual net carbon flux in the terrestrial ecosystems of the Western United States was estimated to be −86.5 TgC/yr, ranging from −162.9 to −13.6 TgC/yr from 2001 to 2005. (Negative values denote a carbon sink.)
    - Forests were the largest carbon sink (62 percent of the average), followed by grasslands/shrublands (30 percent), and agricultural lands (7 percent).
    - The live biomass pool provided about one-third of the carbon sink; the rest was provided by the dead biomass and the SOC pools.
- The ecosystems of the Western United States served as a greenhouse-gas (GHG) sink for three gases: carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). These GHGs accumulated at an estimated −599.1 to −51.3 $TgCO_{2\text{-eq}}$/yr. Overall, the carbon dioxide sink provided by the ecosystems was responsible for about 99 percent of the total GHG flux. The fluxes of nitrous oxide (for which the Western United States was a source) and methane (for which the Western United States was a sink) were relatively very small.

5.2. Introduction

This chapter describes the modeling and analysis of the baseline carbon storage and GHG flux in ecosystems of the Western United States. As indicated by the methodology diagram (figure 1.2 of chapter 1 of this assessment), this component of the assessment uses land-use and land-cover (LULC) mapping and modeling results (chapter 2) and wildland-fire modeling results (chapter 3) as the primary input data in addition to other input data described later in this chapter. The definitions of the ecosystems and the descriptions of the ecoregions are provided in chapters 1 and 2 of this report. See table 2.1 of chapter 2 of this report for definitions of the ecosystems covered in this chapter. The tables in this

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chapter present the results of carbon stock, carbon flux, and GHG fluxes in terms of the following pools: live biomass (both aboveground and belowground), soil organic carbon (SOC; measured in the top 20 cm of the soil layer), and dead biomass (forest litter and dead, woody debris).

Land-use and land-cover change, natural disturbances, and climate change directly alter carbon fluxes and carbon stocks in ecosystems. Although these influences on the carbon cycle have been observed from local to global scales, there is increasing scientific and political interest in regional patterns and causes of terrestrial carbon sources and sinks (Intergovernmental Panel on Climate Change, 2007; Piao and others, 2009; Pan, Birdsey, and others, 2011). Many studies have evaluated the carbon stocks and fluxes in diverse ecosystems and addressed their complicated interactions with climate change, LULC change, and natural disturbances. The U.S. Environmental Protection Agency (EPA) has reported annual carbon fluxes for the United States since 1997 and estimated that U.S. forests sequestered approximately −256 TgC/yr (EPA, 2012). The U.S. Forest Service (USFS) estimated a combined stock of 15,095 TgC in all of the major pools of the Pacific Coast and Rocky Mountain regions for 2005 and that, on average between 2000 and 2008, the forest ecosystems sequestered approximately −43.1 TgC/yr in those two regions (Heath and others, 2011). Hudiburg and others (2011) estimated that the net biome production (NBP) of the forests in the Pacific coastal regions of Washington, Oregon and California averaged −95 $TgCO_{2\text{-eq}}$/yr (−25.9 TgC/yr) between 2001 to 2006. In California, the annual carbon flux for all forests in 2010 was estimated to be −30 $TgCO_{2\text{-eq}}$/yr on the basis of USFS permanent-plot data, forest-growth models, wildland-fire emission estimates, and timber harvest data (California Department of Forestry and Fire Protection, 2010; Robards, 2010). A separate study found that forests and rangelands in California in the 1990s were responsible for a net removal of –7.55 $TgCO_{2\text{-eq}}$ per year from the atmosphere and that agricultural lands were responsible for a net emission of 0.35 $TgCO_{2\text{-eq}}$/yr (S. Brown, Pearson, Dushku, and others, 2004). Citing wildland-fire disturbances and human-induced land-cover changes as two key factors that drive carbon balance in ecosystems of California, J. Liu and others (2011) estimated that California’s natural ecosystems were generally carbon neutral from 1951 to 2000 (with an average NBP of −0.3 TgC/yr), even when the balancing effects of carbon dioxide fertilization and climate-induced increases in the length of the growing season were considered. In Oregon and the rest of the Pacific Northwest, the net ecosystem production (NEP) for forests, agricultural lands, woodlands, grasslands, and shrublands was estimated using forest-inventory data, land-use maps, and a process-based model (D.P. Turner, Ritts, and others, 2011). The study concluded that a decline in forest clearcutting (the result of changes in forest-management policies since the 1990s) has had a profound effect on carbon storage and sequestration, resulting in a switch from a carbon source to a carbon sink around 1990. Some recent regional studies of carbon stocks and fluxes are listed in tables 1.1 and 1.2 of chapter 1 of this report.

As noted in chapter 1, conventional carbon and GHG terminology (such as Chapin and others, 2006) was followed in the assessment. Two concepts are most relevant here. The first is the net ecosystem carbon balance (NECB), which is defined as the net rate of carbon-storage change in ecosystems. The second is the NEP, which is defined as the imbalance between the gross primary production and ecosystem respiration, or the difference between the net primary production and heterotrophic respiration. For this assessment, the NECB was calculated as the carbon storage change of an ecosystem over a period of time. For example, the NECB for year *t* was calculated as the carbon storage in year *t*-1 minus the carbon storage in year *t*. Therefore, a negative value for the NECB indicates a carbon accumulation or sequestration in an ecosystem and a positive value indicates a loss of carbon from the ecosystem, which is the opposite suggested by Chapin and others (2006). The negative value indicates a carbon loss in the atmosphere because of carbon sequestration in ecosystems. This convention is consistent with the Great Plains assessment report (Zhu and others, 2011).

5.3. Input Data and Methods

5.3.1. Input Data for Baseline Simulation Modeling

A variety of input data were needed to model the biogeochemical processes related to carbon stocks, carbon fluxes, and GHG fluxes in the Western United States, including data about climate, LULC, soils, elevation, forest types, biomass, land and forest management, and natural disturbances. The treatment of land-management activities and natural disturbances in ecosystems is discussed in detail in chapter 4 of this report. Table 5.1 lists the input data layers that were used to provide the baseline information for the assessment.

Each of the input datasets was obtained from the indicated data source in table 5.1 and converted to standard spatial and temporal resolutions, projection, and data format. Some examples of input data layers (maps) are provided in figure 5.1.

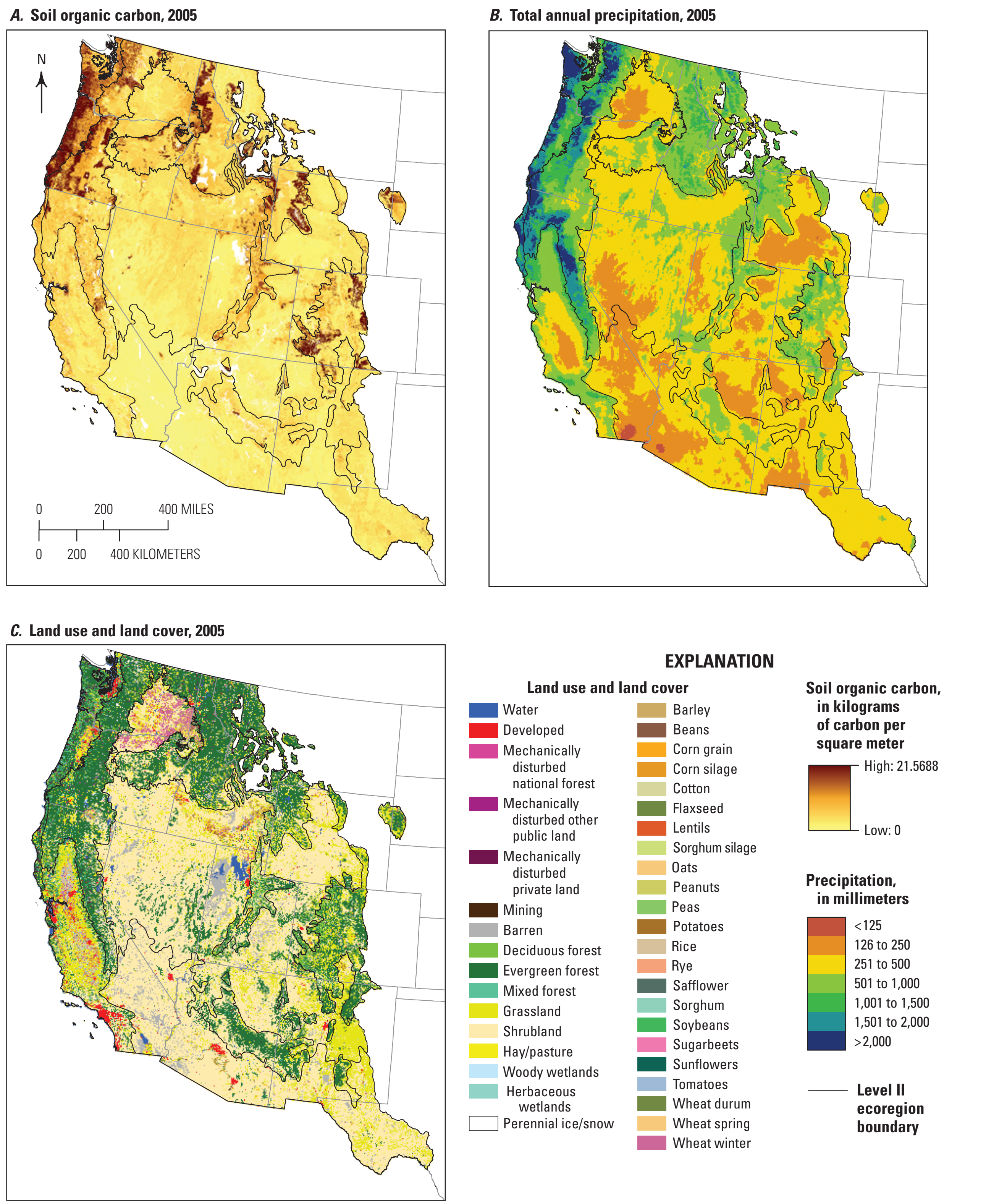


Figure 5.1. Examples of maps showing input data for the Western United States. *A*, Soil organic carbon (SOC) for the top 0 to 5 centimeters of the soil layer; the data were derived from the Soil Survey Geographic (SSURGO) Database (USDA Natural Resources Conservation Service, 2009). *B*, Total annual precipitation in 2005 (PRISM Climate Group, 2012). *C*, Land cover in 2005 from chapter 2 of this report with the agricultural land class downscaled to the crop types (chapter 4 of this report). See figure 1.1 in chapter 1 for ecoregion names.

Table 5.1. Input data used in the baseline-data model runs for the assessment.

[Most of the input data have a 250-m spatial resolution and variable temporal characteristics, although most data cover the first decade of the 21st century. Db 0.33 bar H_2O, the oven-dry weight of the less than 2 mm soil material per unit volume of soil at a water tension of 1/3 bar (as used in the SSURGO database). EDCM, Erosion-Deposition-Carbon Model; FIA, USDA Forest Service's Forest Inventory & Analysis; FIPS, Federal Information Processing Standard; K factor, an erodibility factor that quantifies the susceptibility of soil particles to detachment by water; LP DAAC, Land Processes Active Archive Center; LULC, land use and land cover; mm, millimeter; MODIS, Moderate Resolution Imaging Spectrometer on board NASA's Terra satellite; NASA, National Aeronautics and Space Administration; NPP, net primary productivity; NRCS, USDA's Natural Resources Conservation Service; NTSG, Numerical Terradynamic Simulation Group; PRISM, parameter-elevation regressions on independent slopes model; RPA, U.S. Forest Service Forest and Rangeland Renewable Resources Planning Act of 1974; SSURGO, Soil Survey Geographic Database (NRCS); TPO, timber product output; USDA, U.S. Department of Agriculture]

Data category	Data type	Data source	Model		
			Spreadsheet	EDCM	CENTURY
LULC	LULC classes	Chapter 2 of this report	X	X	
Climate	Monthly minimum and maximum temperature, monthly total precipitation	PRISM Climate Group (2012)		X	X
Soils	Total sand	SSURGO (USDA NRCS, 2009)		X	X
	Total clay			X	X
	Total silt			X	X
	Soil thickness			X	
	Soil organic carbon		X	X	X
	Available water capacity			X	
	Db 0.33 bar H_2O			X	
	K factor				
Forests	Biomass	Geodata (USDA Forest Service, 2012c)	X		
	Stand age	Chapter 2 of this report	X	X	X
	FIA species growth curves, height, diameter, and biomass measurements	USDA FIA (USDA Forest Service, 2012b)	X		
	Timber product output	USDA FIA RPA (USDA Forest Service, 2012b); USDA RPA TPO (USDA Forest Service, 2011)	X		
Crops	Derived crop type	Schmidt and others (2011); Chapter 4 of this report	X	X	X
	USDA crop yield table	USDA National Agricultural Statistics Service (2011)		X	X
	USDA fertilization table	USDA Economic Research Service (2011b)			
	USDA manure table	USDA Economic Research Service (2011a)			
	CTIC tillage table	Conservation Technology Information Center (2011); USDA Economic Research Service (2011a)			
Management	Derived manure	Schmidt and others (2011); Chapter 4 of this report	X	X	X
	Derived tillage	Schmidt and others (2011); Chapter 4 of this report	X	X	X
	Derived fertilizer	Schmidt and others (2011); Chapter 4 of this report	X	X	X
	Irrigation	USGS (2010)	X	X	X

Table 5.1. Input data used in the baseline-data model runs for the assessment.—Continued

[Most of the input data have a 250-m spatial resolution and variable temporal characteristics, although most data cover the first decade of the 21st century. Db 0.33 bar H_2O, the oven-dry weight of the less than 2 mm soil material per unit volume of soil at a water tension of 1/3 bar (as used in the SSURGO database). EDCM, Erosion-Deposition-Carbon Model; FIA, USDA Forest Service's Forest Inventory & Analysis; FIPS, Federal Information Processing Standard; K factor, an erodibility factor that quantifies the susceptibility of soil particles to detachment by water; LP DAAC, Land Processes Active Archive Center; LULC, land use and land cover; mm, millimeter; MODIS, Moderate Resolution Imaging Spectrometer on board NASA's Terra satellite; NASA, National Aeronautics and Space Administration; NPP, net primary productivity; NRCS, USDA's Natural Resources Conservation Service; NTSG, Numerical Terradynamic Simulation Group; PRISM, parameter-elevation regressions on independent slopes model; RPA, U.S. Forest Service Forest and Rangeland Renewable Resources Planning Act of 1974; SSURGO, Soil Survey Geographic Database (NRCS); TPO, timber product output; USDA, U.S. Department of Agriculture]

Data category	Data type	Data source	Model		
			Spreadsheet	EDCM	CENTURY
Elevation	Elevation	USGS (2012b)			
Remote sensing	NPP	M. Zhao and others (2005)		X	X
Wildland fires	Fire size, severity, combustion emissions	Eidenshink and others (2007); Chapter 3 of this report		X	X
Reference information	State and county FIPS codes	U.S. Census Bureau (2012)	X	X	X
Initial conditions	Forest litter biomass	Chapter 5 of this report		X	X
	Aboveground live biomass	Chapter 5 of this report		X	X
	Belowground live biomass	Chapter 5 of this report		X	X
	Deadwood biomass	Chapter 5 of this report		X	X
	Standing wood biomass	Chapter 5 of this report		X	X

5.3.2. The General Ensemble Biogeochemical Modeling System

The General Ensemble Biogeochemical Modeling System (GEMS) (S. Liu and others, 2012) was developed to integrate the well-established biogeochemical models for ecosystems with various spatial databases in order to simulate biogeochemical cycles over large areas. Figure 5.2 shows the overall structure of the GEMS. Some of the key features of the GEMS are described below.

5.3.3. Using the Biogeochemical Model Ensemble to Address Model Biases

All models are imperfect and have simulation biases and errors. As an example, comparison studies by the North American Carbon Program of major biogeochemical models yielded variable estimates of carbon stocks and fluxes (Schwalm and others, 2010; Huntzinger and others, 2012). To minimize biases and errors in the individual models and to quantify the uncertainty of the model outputs, multiple site scale biogeochemical models were encapsulated into the GEMS and used simultaneously to simulate ecosystem dynamics over time and space.

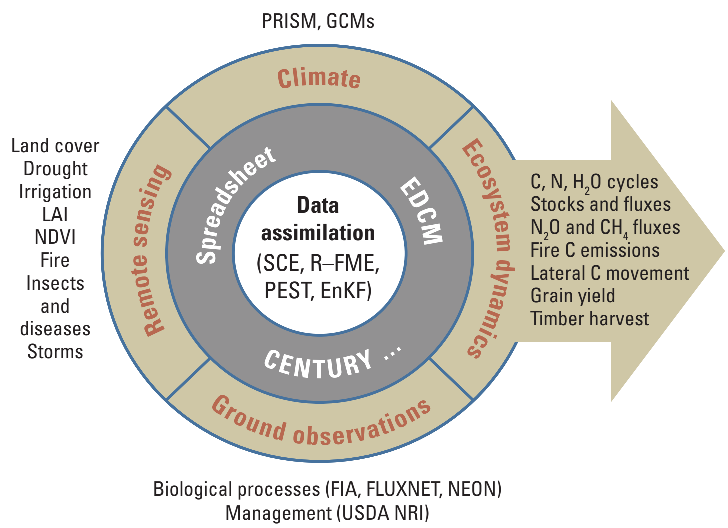


Figure 5.2. Diagram of the General Ensemble Modeling System (GEMS) showing (1) the inputs (climate, remote sensing, and ground observations) and outputs (ecosystem dynamics), (2) the underlying biogeochemical models (spreadsheet, EDCM, and CENTURY), and (3) the data assimilation procedures. Abbreviations are as follows: C, carbon; CH_4, methane; EDCM, Erosion-Deposition-Carbon Model; EnKF, Ensemble Kalman Filter; FIA, U.S. Forest Service's Forest Inventory & Analysis Program; FLUXNET, flux network; GCM, General Circulation Model; H_2O, water; LAI, leaf area index; N, nitrogen; N_2O, nitrous oxide; NDVI, Normalized Difference Vegetation Index; NEON, National Ecological Observatory Network; NRI, Natural Resource Conservation Service's National Resources Inventory; PEST, model independent parameter estimation application; PRISM, parameter-elevation regressions on independent slopes model; R–FME, R Flexible Modeling Environment; SCE, Shuffled Complex Evolution; USDA, U.S. Department of Agriculture.

For this assessment, the CENTURY model (Parton and others, 1987; Parton and others, 1994), the Erosion-Deposition-Carbon Model (EDCM, S. Liu and others, 2003), and a spreadsheet model were incorporated into the GEMS to simulate dynamics of carbon stocks, carbon fluxes, and fluxes of the GHG. These three models were already linked to the GEMS for the assessment of the Great Plains (Zhu and others, 2011).

Two modifications were made to the CENTURY model for the assessment. First, the model's data input and output interface was modified and linked to the GEMS system by using a static FORTRAN library with shared memory to increase the efficiency of the computations. The change did not affect the format of the input and output data for the model. Second, the regional-level NPP and grain-yield calibration process (see section entitled "Calibration of the Model," below) were modified.

Improved modeling of water availability is critical for the predictions of ecosystem productivity and soil organic matter decay because both processes are strongly controlled by soil moisture. The EDCM, which was modified from the CENTURY model, used up to 10 soil layers in a soil profile, compared to the CENTURY model, which used one layer for SOC simulations. In the EDCM, the thickness of the surface soil layer was fixed at the plowing depth of either 20 or 30 cm, whereas the thicknesses of other layers were flexible. The thickness and SOC dynamics of each of the layers were then simulated by modeling the interactions of erosion or deposition, forest-litter input, decomposition, and leaching (Liu and others, 2000; S. Liu and others, 2003). The five SOC pools (metabolic, structural, fast, slow, and passive) in each soil layer were used in the EDCM to characterize the quantity and quality of the SOC, which was similar to the structure for the surface soil depth in the CENTURY model (Parton and others, 1987; Metherell and others, 1993; Parton and others, 1993).

The spreadsheet model (described in Zhu and others, 2010) was developed for this assessment and is based on a simple accounting approach. For SOC, 10 soil layers from the Soil Survey Geographic Database (SSURGO; USDA Natural Resources Conservation Service, 2009) (Sundquist and others, 2009) were used to represent the SOC at each location or pixel. Simplicity in the spreadsheet model was maintained by keeping the SOC unchanged after the model was initialized. For biomass carbon, the grassland/shrubland and agricultural biomass pools were held as constants, whereas the forests biomass pools (including aboveground and belowground live biomass, standing wood, deadwood, forest litter, and other carbon pools) were assigned as a function of forest types (evergreen, broadleaf, and mixed forest) and forest age (both from the LULC modeling described in chapter 2 of this report), as well as the forest age-carbon stock relation. The forest age-carbon stock relation is a set of growth curves specific for forest types (such as softwood, hardwood, and mixed) and FIA units. Derived from FIA inventory data, the relation describes quantitatively the amount of biomass carbon as a function of average forest age. Each forest type has a distinct forest age-carbon stock relation unless the number of FIA plots was not large enough to derive such a relation. In this case, a representative regional forest age-carbon stock relation was used.

On the basis of the forest age-carbon stock relation (growth curve) discussed above and the LULC maps, the effects of either forest aging or clearcutting were quantified in the spreadsheet model. The spreadsheet model, however, was not intended to quantify the effects of climate variability and change or of carbon-dioxide fertilization on carbon. The algorithms for estimating wildland-fire emissions were not implemented in the spreadsheet model for this assessment. Following a recommendation by the Intergovernmental Panel on Climate Change, the spreadsheet model estimated methane and nitrous-oxide fluxes for different LULC classes using emission factors that were compiled from an extensive review of the literature (Mosier and others, 1997; Kessavalou and others, 1998; Gleason and others, 2007; Sainju, 2008; Liebig and others, 2010). Emission factors were compiled and synthesized by ecosystem type and ecoregion for this assessment.

Although the biogeochemical models in the GEMS have different output variables, their common output variables include gross and net primary productivity (GPP, NPP), autotrophic and heterotrophic respiration, grain production, and carbon stock estimates over time in vegetation and soil pools for terrestrial ecosystems.

5.3.4. Model Initializations

The following soil properties were initialized on the basis of data from the SSURGO database (USDA Natural Resources Conservation Service, 2009): soil thickness, organic carbon storage, texture (fractions of sand, silt, and clay), bulk density, and drainage. Forest biomass carbon pools (aboveground and belowground live biomass, or dead biomass consisting of forest litter and dead, woody debris) were initialized using the initial forest-age map (derived from FIA data; USDA Forest Service, 2012b), forest type (evergreen, broadleaf, and mixed), and the forest age-carbon stock relation. For consistency and to avoid potential errors, the initialization of the SOC and biomass was done using the spreadsheet model, and its outputs for 1992 (the first year of the model simulations) were then read directly by the CENTURY model and the EDCM as their initial conditions. The years from 1992 to 2000 were used as a period of calibrations to achieve relative stabilization (that is, model spin-up) for the EDCM and CENTURY simulations.

5.3.5. Model Calibration

Models usually contain parameters that (1) cannot be determined by using local field measurements or (2) can be measured locally but cannot be used regionally because of the effects of the scale of the measurements. Models are calibrated by adjusting such model parameters to optimize the agreement between observation and simulation. The observed data available for calibrating carbon-flux model runs from 2001 to 2005 included (1) county-based grain-yield-survey data by crop type, published by the USDA (USDA, National Agricultural Statistics Service, 2011); and (2) 250-m resolution NPP data from the MODIS for other LULC types such as forests and grasslands (Zhao and others, 2005). The MODIS NPP was found to lack consistent performance for calibrating crop production on agricultural lands and, therefore, crop yields from the USDA were used. An automated calibration was implemented for the EDCM using the Shuffled Complex Evolution (SCE) (Duan and others, 1992) and an R software package, Flexible Modeling Environment (R–FME) (Soetaert and Petzoldt, 2010; Wu and Liu, 2012). On the other hand, manual calibration was used for the CENTURY model. The potential maximum production parameter (PRDX) was adjusted by comparing the modeled grain yield and the forest NPP with the USDA's county-level statistics of grain yield and county-level, MODIS-derived NPP from 2001 to 2005.

5.3.6. Model Validation

Maps, binned scatterplots, and correlation plots were generated for different ecosystems in each ecoregion of the Western United States in order to compare the simulated results of the three models run within the GEMS with observational data (for example, the USDA FIA biomass estimate, an estimate from the National Biomass and Carbon Dataset 2000 (Kellndorfer and others, 2004), the MODIS-derived NPP (Zhao and others, 2005), and the USDA grain yield (USDA, National Agricultural Statistics Service, 2011) for 2006, 2008, and 2010. Simple linear-regression modeling, the coefficient of determination, and the root mean square error (RMSE) between the observed and modeled data were calculated to evaluate the performance of the models. Some of the results of the validation are shown in figure 5.3 and table 5.2.

5.3.7. Model Run Setup

The simulation models were run for every year from 1992 to 2050, with the years 1992 to 2000 used as model spin-up, 2001 to 2005 used as the baseline period (this chapter), and 2006 to 2050 as the projection period (chapter 9). A total of three GEMS simulations (by the spreadsheet model, CENTURY model, and the EDCM) were used to support the assessment of carbon dynamics during the baseline period. As noted previously, the purpose of using multiple models was to minimize the potential biases and errors that were inherent in the models and to provide an opportunity to quantify structure-related uncertainties in the models.

Before the full-resolution or wall-to-wall simulations were run to produce spatial data products for this assessment, a systematic sampling approach was used first to improve the performance of the model simulations. Both the EDCM and the CENTURY model were run with a 10 × 10 systematic subsample factor to ensure adequate time for processing, generating statistics, and calibrating the estimates. Therefore, for these two models, the results reported here were based on a systematic sample of 1 percent of the total pixels. A comparison of the sampling results with the full-resolution simulations indicated that the sampling approach provided the same regional statistics as the full-resolution simulation.

Table 5.2. Comparison of the three different biogeochemical models in the General Ensemble Modeling System (GEMS) based on aggregated results at the county level, for 2006.

[MODIS NPP, net primary productivity derived from the Moderate Resolution Imaging Spectroradiometer; NBCD, National Biomass and Carbon Dataset (Kellndorfer and others, 2004); USDA FS, U.S. Forest Service; R^2, coefficient of determination; RMSE, root mean squared error; USDA U.S. Department of Agriculture].

Observation	Model	Land use or land cover	RMSE	R^2
NBCD live biomass	Spreadsheet	Forests	7.312	0.61
USDA FS live biomass	Spreadsheet	Forests	4.376	0.90
MODIS NPP	CENTURY	Forests	0.216	0.95
MODIS NPP	EDCM	Forests	0.167	0.98
MODIS NPP	CENTURY	Grasslands/shrublands	0.100	0.74
MODIS NPP	EDCM	Grasslands/shrublands	0.038	0.96
USDA grain yield	CENTURY	Winter wheat	0.003	0.97
USDA grain yield	EDCM	Winter wheat	0.005	0.94

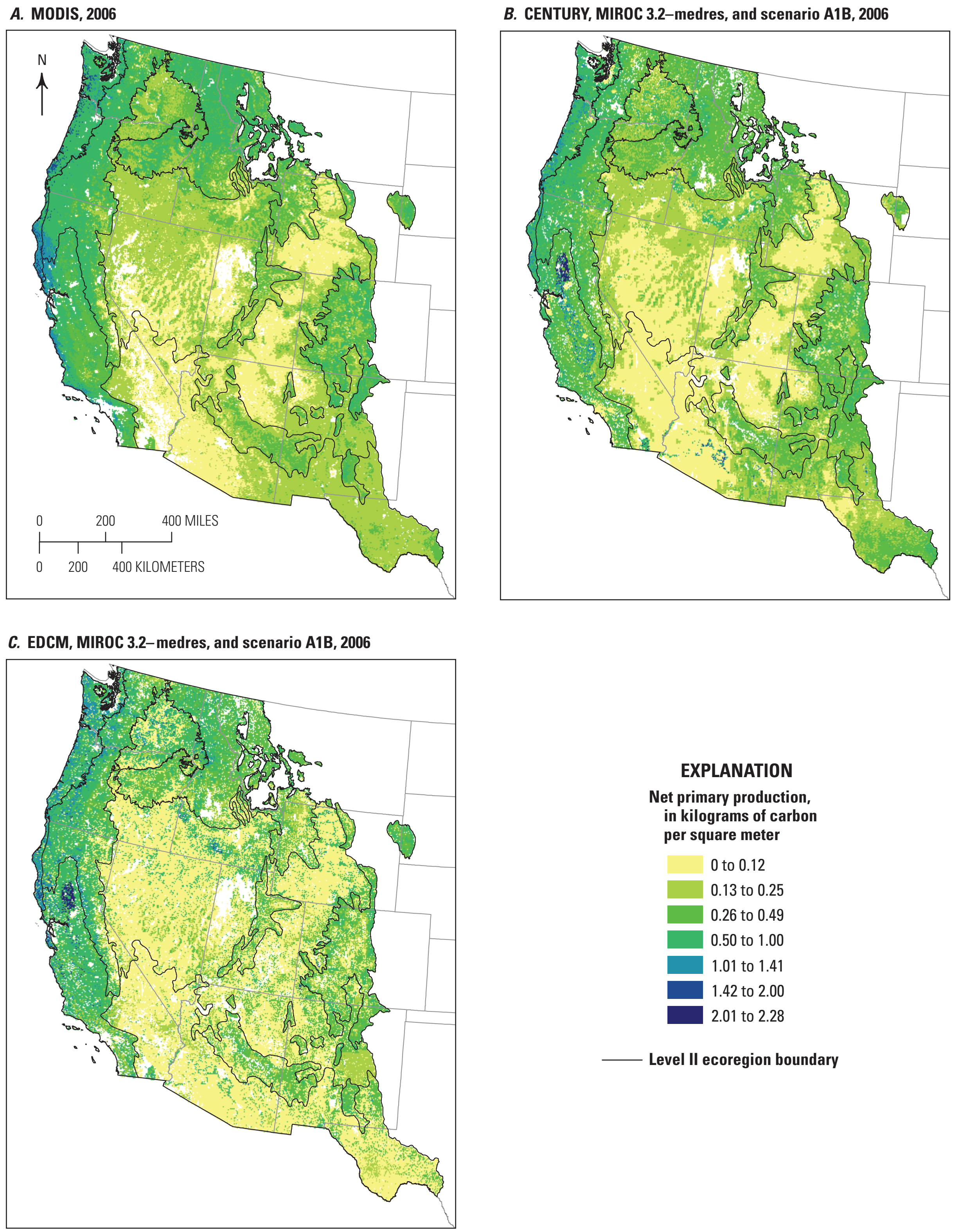


Figure 5.3. Maps showing a comparison of net primary productivity (NPP) in the Western United States for 2006 estimated by three different methods and tools . *A*, Data from the Moderate Resolution Imaging Spectroradiometer (MODIS). *B,* The CENTURY model run under IPCC–SRES scenario A1B and using the MIROC 3.2-medres general circulation model. *C*, The Erosion-Deposition-Carbon Model (EDCM) run under IPCC–SRES scenario A1B and using the MIROC 3.2-medres general circulation 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 version 3.2, medium resolution. See figure 1.1 in chapter 1 for ecoregion names.

5.4. Results and Discussion

5.4.1. Carbon Stocks in 2005

The magnitude and spatial pattern of the carbon stock estimated from 2001 to 2005 remained relatively stable, therefore the estimates for 2005 are presented here. The map in figure 5.4*A* shows the spatial distribution of the mean amount of carbon stored (based on the average of three carbon-stock maps from the three models) in all of the ecosystems of the Western United States in 2005, and the standard deviation of the results, which indicates a measure of uncertainty. The total carbon stored included carbon in live biomass, SOC in the top 20 cm of the soil layer, and dead biomass. The map indicates that forests in the Marine West Coast Forest and Western Cordillera ecoregions stored the most carbon, whereas there was relatively less carbon stored in the grasslands/shrublands-dominated Cold Deserts and Warm Deserts ecoregions and in the mixed agricultural lands, grasslands/shrublands, and forests of the Mediterranean California ecoregion. The standard deviation of the estimates of the three models was generally higher in the coastal forests and in the Cascades, which is likely the result of the high biomass levels and logging rates. The uncertainties in the carbon stock were lower in the interior forests, where the biomass levels and logging rates were lower. The uncertainties were also lower in landscapes dominated by grasslands/shrublands.

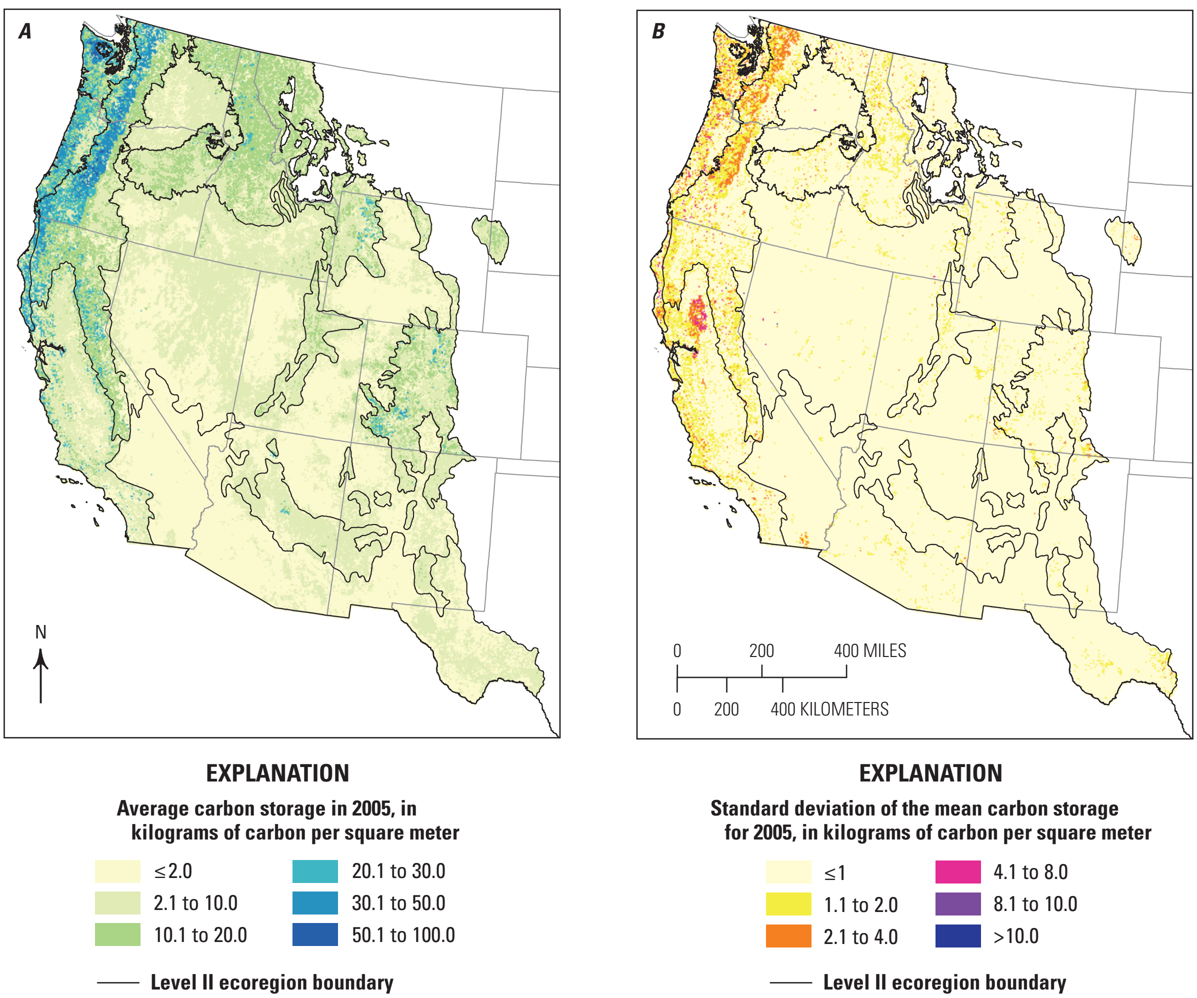


Figure 5.4. Maps showing the mean amount of carbon stored and the standard deviation for 2005. *A*, The estimated mean amount of carbon stored in 2005, which was derived by averaging the results from the three General Ensemble Modeling System (GEMS) models (spreadsheet, CENTURY, and EDCM). *B*, The standard deviation of the three modeling results around the mean. EDCM, Erosion-Deposition-Carbon Model. See figure 1.1 in chapter 1 for ecoregion names.

Annual maps of estimated carbon stocks by the terrestrial ecosystems and ecoregions from 2001 to 2005 were produced using the three models, as previously described. At the regional scale, temporal variability remained relatively small between the years. Table 5.3 gives the range (minimum to maximum) of the estimated amounts of carbon stored as simulated by the three models (spreadsheet, EDCM, and CENTURY) for 2005, the last year of the baseline conditions. During 2005, the average total amount of carbon stored in the entire Western United States was estimated to be 13,920 TgC (ranging from 12,418 to 15,461 TgC). The estimates for the Western United States are about 8 percent lower than a previously published estimate of 15,095 TgC for all major carbon pools in the Pacific Coast and Rocky Mountain regions in 2005 (J.E. Smith and Heath, 2008). Among all the ecoregions, the Western Cordillera stored the most carbon at over 8,162 TgC (59 percent), followed by the Cold Deserts (19 percent), the Marine West Coast Forest (11 percent), Mediterranean California (6 percent), and the Warm Deserts (5 percent). Live biomass, SOC, and dead biomass accounted for 39.0 percent, 38.3 percent, and 22.7 percent, respectively, of the total carbon stored in the Western United States. In terms of ecosystems, forests, grasslands/shrublands, and agricultural lands stored 69 percent, 25 percent, and 4.3 percent, respectively, of the total carbon. Among the different ecosystems, forests stored the most carbon in the Western Cordillera, Marine West Coast Forest, and Mediterranean California ecoregions; grasslands/shrublands stored the most carbon in the Cold Deserts and Warm Deserts ecoregions.

Using table 5.3, the carbon density (that is, the amount of carbon stored per unit of area) could be derived by ecosystem and ecoregion. Forests stored the most carbon in the Marine West Coast Forest (21.9 kgC/m^2), followed by Mediterranean California (14.9 kgC/m^2), the Western Cordillera (13.0 kgC/m^2), the Cold Deserts (6.7 kgC/m^2), and the Warm Deserts (5.2 kgC/m^2). The ecoregions that had highest and lowest carbon densities in grasslands/shrublands were the Marine West Coast Forest at 6.6 kgC/m^2 and the Warm Deserts at 1.5 kgC/m^2, respectively. Although agricultural lands covered only a small percentage of the Western United States, most of this ecosystem stored more carbon than grasslands/shrublands. For example, in the Western Cordillera ecoregion, the carbon density in the top 20 cm of soil for forests, grasslands/shrublands, and agricultural lands was 3.3, 2.4, and 3.9 kgC/m^2, respectively. Further results for each ecoregion are provided below.

5.4.1.1. Western Cordillera

The Western Cordillera is the second largest ecoregion in the Western United States. In 2005, the average total amount of carbon stored in this ecoregion was estimated to be 8,163 TgC (ranging from 7,488 to 8,793 TgC), of which an average of 43 percent was in live biomass, 32 percent in soil, and 25 percent in dead biomass. Among the different ecosystems, forests occupied 63 percent of the total land area and stored an average of 87 percent of the total carbon stock (7,123 TgC or 13.0 kgC/m^2). Grasslands/shrublands occupied 32 percent of the total land area but only stored an average of 11 percent of the total carbon stock (923 TgC, or 3.3 kgC/m^2). Agricultural lands occupied a small area of the ecoregion (2 percent) and stored only an average of 1 percent of the total carbon stock (72 TgC, or 4.3 kgC/m^2).

5.4.1.2. Marine West Coast Forest

In 2005, the average total amount of carbon stored in the Marine West Coast Forest was estimated to be 1,534 TgC (ranging from 1,447 to 1,646 TgC), of which an average of 48 percent was in live biomass, 33 percent in soil, and 19 percent in dead biomass. Forests stored the most carbon in the ecoregion (an average of 1,415 TgC, 92 percent of the total), followed by agricultural lands (an average of 67 TgC, 4 percent of the total) and grasslands/shrublands (an average of 30 TgC, 2 percent of the total). This small coastal ecoregion had the highest percentage of its total land area covered by forests (68 percent) and those forests had the highest average carbon density (21.9 kgC/m^2) of any forests in the five ecoregions. The carbon densities in grasslands/shrublands (6.6 kgC/m^2) and agricultural lands (6.4 kgC/m^2) were also higher than the carbon densities in the same ecosystems in the other ecoregions.

5.4.1.3. Cold Deserts

The Cold Deserts ecoregion is the largest in the Western United States and was dominated by the grasslands/shrublands ecosystem (76 percent of the total land area). In 2005, the average total amount of carbon stored in this ecoregion was estimated to be 2,651 TgC (ranging from 2,267 to 3,124 TgC), of which an average of 23 percent was in live biomass, 58 percent in soil, and 18 percent in dead biomass. The grasslands/shrublands stored the most carbon in the ecoregion (an average of 1,672 TgC, 63 percent of the total), followed by forests (an average of 647 TgC, 23 percent of the total) and agricultural lands (an average of 282 TgC, 18 percent of the total). The average total carbon density in this ecoregion was 2.5 kgC/m^2, which was lower than that of the Western Cordillera (9.4 kgC/m^2) and the Marine West Coast Forest (16.1 kgC/m^2).

5.4.1.4. Warm Deserts

The vegetation in the extremely arid Warm Deserts ecoregion was also dominated by the grasslands/shrublands ecosystem (87 percent of total land area). In 2005, the average total carbon stored in this ecoregion was estimated to be only 700 TgC (ranging from 525 to 921 TgC), of which 26 percent

Table 5.3. Minimum and maximum estimates of carbon stored in the Western United States in 2005, by carbon pool for each ecoregion and ecosystem.

[Only soil organic carbon (SOC) in the top 20 cm of the soil layer was calculated. 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 (TgC)		Dead biomass (TgC)		Total (TgC)	
			Min	Max	Min	Max	Min	Max	Min	Max
Western Cordillera	Forests	546,533	3,304.6	3,689.4	1,599.5	1,887.7	1,398.0	2,348.2	6,648.2	7,557.6
	Grasslands/shrublands	277,874	71.5	148.6	629.1	718.9	0.0	222.5	745.8	1,090.0
	Agricultural lands	16,722	0.1	2.4	64.4	65.3	0.0	8.1	67.7	72.6
	Wetlands	3,656	4.7	5.2	13.8	18.4	2.4	5.7	23.2	28.8
	Other lands	27,469	0.2	0.4	1.9	43.9	0.0	0.7	2.9	44.1
	Total	872,253	3,381.1	3,846.0	2,308.7	2,734.2	1,400.4	2,585.2	7,487.7	8,793.1
Marine West Coast Forest	Forests	64,601	696.0	829.8	398.7	416.4	235.8	336.2	1,347.6	1,510.5
	Grasslands/shrublands	4,542	1.7	4.0	19.1	23.4	0.0	6.0	20.7	32.7
	Agricultural lands	10,418	0.1	1.5	61.1	64.6	0.0	6.0	65.9	67.2
	Wetlands	588	2.3	2.8	3.0	3.8	0.4	1.0	5.6	7.1
	Other lands	15,262	0.0	1.0	4.0	28.4	0.0	2.2	7.0	28.4
	Total	95,411	700.1	839.0	485.8	536.6	236.2	351.5	1,446.9	1,645.9
Cold Deserts	Forests	97,180	269.4	293.6	179.6	213.5	131.7	222.2	638.8	685.1
	Grasslands/shrublands	804,658	275.1	371.8	960.1	1,191.0	0.0	519.6	1,370.9	2,066.1
	Agricultural lands	81,191	0.1	12.9	222.0	254.3	0.0	41.9	234.9	296.3
	Wetlands	4,635	2.6	3.7	14.9	20.0	1.9	5.3	21.0	27.9
	Other lands	68,392	0.0	0.3	2.7	49.0	0.0	0.3	3.0	49.0
	Total	1,056,055	547.2	682.4	1,379.3	1,727.9	133.6	789.4	2,268.6	3,124.4
Warm Deserts	Forests	8,084	20.1	22.7	7.3	10.4	8.7	19.8	39.9	49.8
	Grasslands/shrublands	403,390	120.4	193.5	300.3	418.1	0.0	204.1	470.7	815.7
	Agricultural lands	11,334	0.0	2.0	10.7	25.4	0.0	8.6	12.6	35.5
	Wetlands	326	0.2	0.3	0.3	0.5	0.0	0.6	0.5	1.1
	Other lands	42,150	0.0	0.2	0.8	18.4	0.0	0.2	0.9	18.9
	Total	465,285	140.6	218.6	319.4	472.8	8.8	233.3	524.6	921.0
Mediterranean California	Forests	29,945	250.9	296.0	56.9	85.7	88.3	119.0	424.9	469.8
	Grasslands/shrublands	74,294	28.1	37.2	125.9	179.9	0.0	62.9	154.0	279.8
	Agricultural lands	41,046	0.0	7.4	94.2	146.6	0	35.1	101.6	188.4
	Wetlands	910	0.5	0.9	4.4	5.0	0.4	1.5	5.8	7.0
	Other lands	23,259	0.0	0.4	3.9	31.2	0.0	0.3	4.3	31.2
	Total	169,455	279.5	341.8	285.3	448.4	88.7	218.8	690.5	976.3
Western United States (total)	Forests	746,343	4,541.0	5,131.4	2,242.0	2,613.8	1,862.6	3,045.5	9,099.4	10,272.8
	Grasslands/shrublands	1,564,759	496.7	755.0	2,034.4	2,531.2	0.0	1,015.1	2,762.0	4,284.2
	Agricultural lands	160,711	0.3	26.1	452.4	556.2	0.0	99.7	482.7	660.0
	Wetlands	10,114	10.2	12.8	36.3	47.7	5.1	14.1	56.1	71.9
	Other lands	176,532	0.2	2.4	13.4	171.0	0.0	3.8	18.1	171.7
	Total	2,658,459	5,048.5	5,927.8	4,778.5	5,919.9	1,867.7	4,178.2	12,418.3	15,460.6

was in live biomass, 56 percent in soil, and 18 percent in dead biomass. The grasslands/shrublands stored the most carbon in the ecoregion (623 TgC, an average of 89 percent of total), followed by forests (42 TgC, an average of 6 percent of total) and agricultural lands (24 TgC, an average of 3 percent of total). The carbon densities were the lowest among all of the ecoregions (5.1, 1.5, and 2.1 kgC/m^2 for forests, grasslands/shrublands, and agricultural lands, respectively).

5.4.1.5. Mediterranean California

In 2005, the Mediterranean California ecoregion stored an estimated average total carbon stock of 873 TgC (ranging from 691 to 976 TgC), of which 34 percent was in live biomass, 45 percent was in soil, and 20 percent was in dead biomass. Forests stored half of the total carbon stock (448 TgC, an average of 51 percent of total), followed by grasslands/shrublands (246 TgC, an average of 28 percent of total) and agricultural lands (157 TgC, an average of 18 percent of total). The percentage of agricultural land in this ecoregion was high compared to the other ecoregions in the Western United States. The estimated carbon densities were approximately 15.0, 3.3, and 3.8 kgC/m^2 for forests, grasslands/shrublands, and agricultural lands, respectively).

5.4.1.6. Discussion of Baseline Carbon Storage

For the five western ecoregions in 2005, the estimated average amount of carbon stored in 74.6 megahectares (Mha) of forest ecosystems, as mapped and modeled using the assessment methodology, was approximately 9,675 TgC (ranging from 9,099 to 10,273 TgC), distributed in live biomass (4,674 TgC, ranging from 4,541 to 5,131 TgC), the top 20 cm of the soil (SOC; 2,503 TgC, ranging from 2,242 to 2,614 TgC), and dead biomass (2,498 TgC, ranging from 1,863 to 3,046 TgC). The average per-unit-of-area forest carbon stock density estimates were derived from the total forest carbon stock and total forest area estimates and ranged from 12.2 to 13.8 kgC/m^2 with a mean of 13.0 kgC/m^2. As a comparison, a separate analysis using the USFS FIA carbon stock and forest area estimates (Brad Smith, USDA Forest Service, unpub. data, 2010) suggested a total carbon stock of 13,579 TgC in 93.6 Mha of forested area (or an average of 14.5 kgC/m^2) in the same five ecoregions. The differences in estimates of the total carbon stock and stock density between the two studies may be primarily attributed to (1) the different amount of area that was categorized as forest, which was derived on the basis of different forest definitions and mapping or modeling approaches (Nelson and Vissage, 2005; chapter 2 of this report) and (2) the fact that only carbon in the top 20 cm of the soil layer was modeled as SOC in this assessment, compared to the FIA SOC estimate, which was based on the top 1 m of the soil layer.

5.4.2. Baseline Carbon Flux from 2001 to 2005

The magnitude and spatial distribution of the mean net carbon fluxes across the Western United States are shown in figure 5.5, which indicates that the forested regions of the Pacific Coast gained the most carbon. The standard deviations were generally positively correlated with carbon gains, as expected.

Table 5.4 gives the range (minimum and maximum) of the net carbon flux in the Western United States from 2001 to 2005 by ecoregion, ecosystem, and carbon pool (live biomass, soil, and dead biomass). The estimated overall carbon-sequestration rate ranged from −162.9 to −13.6 TgC/yr with an average of −86.6 TgC/yr, of which −27.6 TgC/yr may be attributed to live biomass accumulation and −58.9 TgC/yr to the dead biomass and soil carbon pools. The forest ecosystem was the largest carbon sink (62 percent of the total), followed by grasslands/shrublands (30 percent) and agricultural lands (7 percent). In forests, the major portion of sequestered carbon was allocated to live biomass. In grasslands/shrublands and agricultural lands, carbon accumulated mainly in soil and dead biomass.

On a per-unit-of-area basis, the estimated average carbon net flux by forests, grasslands/shrublands, and agricultural lands was −72, −16, and −38 gC/m^2/yr, respectively, from all carbon pools. Of these estimates, the soil carbon pool was responsible for –23, –10, and –26 gC/m^2/yr, respectively for the ecosystems. The gain by soil in agricultural lands was higher than the gain by soil in grasslands/shrublands. Two possible reasons for the higher gain by soil in agricultural lands are increased biomass productivity due to genetically improved seeds and improved management practices including fertilizer and (or) irrigation, which may have lead to the overall higher yield of biomass than in the grasslands/shrublands. Although both the Western Cordillera and the Cold Deserts ecoregions were considered to be carbon sinks from 2001 to 2005, the grasslands/shrublands in these two ecoregions were estimated to have lost carbon in the live biomass at an average estimated rate of 0.23 and 3.82 TgC/yr, respectively. Further descriptions of the net carbon fluxes for each ecoregion are provided below.

5.4.2.1. Western Cordillera

From 2001 to 2005, the average estimated net carbon flux in the Western Cordillera was −50 TgC/yr (ranging from −86.1 to −19.1 TgC/yr), of which 48 percent was allocated to live biomass, 37 percent to soil, and 15 percent to dead biomass. Among the different ecosystems, forests sequestered an estimated average of −43 TgC/yr (85 percent of total), grasslands/shrublands sequestered an estimated average of −7 TgC/yr (14 percent of total), and agricultural lands sequestered an estimated average of –0.22 TgC/yr (less than 1 percent of total).

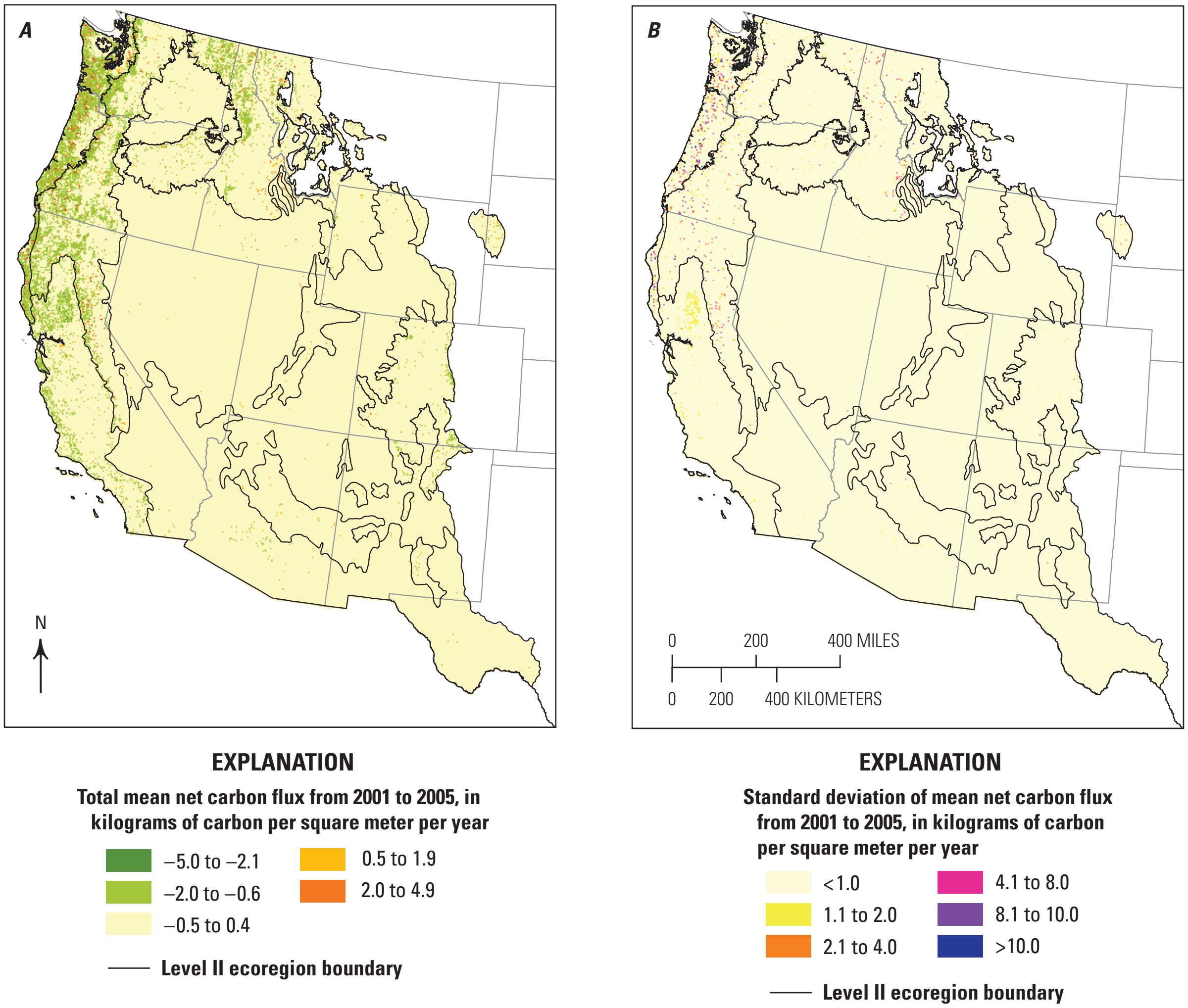


Figure 5.5. Maps showing carbon flux in ecosystems of the Western United States. *A*, The mean net carbon flux derived from each of the three models (spreadsheet, CENTURY, and EDCM) and averaged for the baseline years, 2001 to 2005. *B*, The standard deviation of the three models for the baseline years. Negative values indicate net carbon gains and positive values indicate net carbon losses. EDCM, Erosion-Deposition-Carbon Model. See figure 1.1 in chapter 1 for ecoregion names.

5.4.2.2. Marine West Coast Forest

From 2001 to 2005, the estimated average net carbon flux in the Marine West Coast Forest was −3.8 TgC/yr (ranging from −6.9 to −1.0 TgC/yr). Forests sequestered an estimated average of −3.4 TgC/yr, followed by grasslands/shrublands at an estimated average of −0.5 TgC/yr. Agricultural lands lost carbon to the atmosphere at a low estimated average rate of 0.04 TgC/yr, mostly from soil organic matter.

5.4.2.3. Cold Deserts

From 2001 to 2005, the estimated average net carbon flux in the Cold Deserts ecoregion was −12.3 TgC/yr (ranging from −32.6 to 5.7 TgC/yr). In forests, live biomass and soil sequestered carbon (estimated average rate of −3.72 TgC/yr) but dead biomass lost carbon (estimated average rate of 0.77 TgC/yr). Conversely, live biomass in grasslands/shrublands lost carbon (estimated average rate of 3.82 TgC/yr) but soil and dead biomass sequestered carbon (estimated average rate of −11.1 TgC/yr). Agricultural lands sequestered carbon at an estimated average rate of −1.82 TgC/yr.

5.4.2.4. Warm Deserts

The Warm Deserts ecoregion was dominated by grasslands/shrublands (87 percent of total land area). From 2001 to 2005, the estimated average net carbon flux was −6.8 TgC/yr (ranging from −18.6 to 2.9 TgC/yr); carbon sequestration occurred mainly in the grasslands/shrublands ecosystem. Agricultural lands also sequestered an estimated average of −0.84 TgC/yr while forests only gained carbon at −0.18 TgC/yr.

Table 5.4. Minimum and maximum estimates of net carbon flux in the Western United States from 2001 to 2005, by carbon pool for each ecoregion and ecosystem.

[Negative numbers indicate carbon sequestration; positive numbers indicate a loss of carbon to the atmosphere. Only soil organic carbon (SOC) in the top 20 cm of the soil layer was calculated. km^2, square kilometers; max, maximum; min, minimum; TgC/yr, teragrams of carbon per year, or 10^{12} grams of carbon per year]

Ecoregion	Ecosystem	Area (km^2)	Net carbon flux (TgC/yr)							
			Live biomass		Soil		Dead biomass		Total	
			Min	Max	Min	Max	Min	Max	Min	Max
Western Cordillera	Forests	546,533	−29.7	−16.5	−21.7	0	−18.9	9.4	−70.3	−19.6
	Grasslands/shrublands	277,874	−0.5	1.1	−7.7	0.2	−6.4	0	−14.6	0.2
	Agricultural lands	16,722	0	0	−0.1	0.1	−0.2	0	−0.4	0
	Wetlands	3,656	−0.1	0	−0.5	−0.1	−0.1	0	−0.7	−0.1
	Other lands	27,469	0	0	−0.2	0.4	0	0	−0.2	0.4
	Total	872,253	−30.3	−15.4	−30.2	0.6	−25.6	9.4	−86.1	−19.1
Marine West Coast Forest	Forests	64,601	−2.4	−0.4	−2.8	0.2	−1.7	0.3	−6	−1.3
	Grasslands/shrublands	4,542	−0.2	0	−0.4	0	−0.1	0	−0.7	0
	Agricultural lands	10,418	0	0	0.1	0.2	−0.1	0	0	0.1
	Wetlands	588	0	0.1	−0.1	0	0	0	0	0
	Other lands	15,262	0	0	−0.2	0.2	0	0.1	−0.2	0.2
	Total	95,411	−2.6	−0.3	−3.4	0.5	−1.9	0.4	−6.9	−1
Cold Deserts	Forests	97,180	−4.6	−1.5	−1.6	0.3	−1.6	3.5	−7.8	1.5
	Grasslands/shrublands	804,658	0	5.5	−13.4	0.1	−10.9	0	−20.9	3.8
	Agriculture	81,191	−0.2	0	−2.1	0.2	−1	0	−3	0
	Wetlands	4,635	0	0	−0.5	0	−0.1	0	−0.6	0
	Other lands	68,392	0	0	−0.3	0.4	0	0	−0.3	0.4
	Total	1,056,055	−4.8	4.1	−17.8	1	−13.6	3.5	−32.6	5.7
Warm Deserts	Forests	8,084	−0.3	−0.1	−0.1	0	−0.2	0.4	−0.6	0.2
	Grasslands/shrublands	403,390	−3	2.8	−5.4	0.1	−7.7	0.7	−16.1	2.7
	Agricultural lands	11,334	0	0	−1.1	0	−0.7	0	−1.8	0
	Wetlands	326	0	0	0	0	0	0	0	0
	Other lands	42,150	0	0	−0.1	0.1	0	0	−0.1	0
	Total	465,285	−3.3	2.7	−6.7	0.2	−8.6	1.1	−18.6	2.9
Mediterranean California	Forests	29,945	−2.9	−2.3	−2.1	0	−1.8	−0.1	−6.1	−2.6
	Grasslands/shrublands	74,294	−0.6	0.1	−5	0.2	−2.2	0	−6.4	0.3
	Agricultural lands	41,046	0	0.1	−4.3	0.1	−1.3	0	−5.6	0.2
	Wetlands	910	0	0	−0.1	0.1	0	0	−0.1	0.1
	Other lands	23,259	0	0	−0.4	−0.1	0	0	−0.4	−0.1
	Total	169,455	−3.6	−2.1	−11.9	0.2	−5.4	0	−18.7	−2.2
Western United States (total)	Forests	746,343	−39.8	−20.8	−28.3	0.6	−24.1	13.4	−90.7	−21.8
	Grasslands/shrublands	1,564,759	−4.3	9.5	−31.9	0.6	−27.3	0.7	−58.7	7
	Agricultural lands	160,711	−0.3	0.1	−7.5	0.5	−3.3	0	−10.8	0.3
	Wetlands	10,114	−0.1	0.2	−1.2	−0.1	−0.3	0	−1.5	0
	Other lands	176,532	−0.1	0	−1.1	0.9	−0.1	0.1	−1.2	0.9
	Total	2,658,459	−44.6	−11.1	−70	2.5	−55	14.2	−162.9	−13.6

5.4.2.5. Mediterranean California

From 2001 to 2005, the estimated average net carbon flux in the Mediterranean California ecoregion was −13.7 TgC/yr (ranging from −18.7 to −2.2 TgC/yr). The total rate of carbon sequestration was attributed to forests (−4.8 TgC/yr), grasslands/shrublands (−5.3 TgC/yr), and agricultural lands (−3.3 TgC/yr).

5.4.2.6. Discussion of Baseline Net Carbon Flux

In the Western United States, the evergreen forest of the Pacific Coast was the most productive ecosystem and sequestered a significant amount of carbon. D.P. Turner, Gockede, and others (2011) estimated that the per-unit-of-area NEP of Oregon's coastal forests (an average of private and public forest) during 2007 was around −75 $gC/m^2/yr$. In this assessment, the average estimated net carbon flux for the Marine West Coast Forest ecoregion in the baseline period was −52 $gC/m^2/yr$ on a per-unit-of-area basis, about 30 percent lower. For the five western ecoregions, the estimated average net carbon flux in forests was −54 TgC/yr (ranging from −90.7 to −21.8 TgC/yr), which is comparable to an estimate by Heath and others (2011) of −43.1 TgC/yr (ranging from 24.9 to −111.2 TgC/yr) for the years 2000 to 2008. The average annual net carbon flux estimates from the two studies may be expressed as per-unit-of-area carbon flux: −72.4 $gC/m^2/yr$ from this assessment and −93.8 $gC/m^2/yr$ from Heath and others (2011).

Estimates of net carbon flux in California's agricultural lands were variable. Kroodsma and Field (2006) estimated that California's agricultural lands sequestered an average of −19 $gC/m^2/yr$ between 1980 and 2000. For this assessment, however, the Mediterranean California ecoregion (not the entire state of California) was estimated to have sequestered an average of −81 $gC/m^2/yr$ (−3.3 TgC/yr over 41,046 km^2) during the baseline period. The large gap between the results of this assessment and those of the earlier studies can be attributed to several observations. First, Kroodsma and Field (2006) estimated that the conversion of annual crops to vineyards or orchards generated a carbon sink of −68 to −85 $gC/m^2/yr$, which was very close to the estimate in this assessment. Second, they also indicated that rice fields sequestered −55 $gC/m^2/yr$ due to a reduction of field burning. This assessment did not include field burning of crop residue, and therefore the estimated carbon sink in this assessment should be high.

As noted previously (see section entitled "Model Run Setup"), the purpose of using multiple models on the GEMS platform was to provide an opportunity to quantify uncertainties related to model structures and inherent biases and errors. Table 5.5 shows the average estimates of carbon stocks and carbon fluxes derived by each of the three models for each of the five ecoregions. A variability value (in percent) was also calculated by dividing the range of the minimum and maximum estimates of the subset by their mean, and multiplying by 100.

5.4.3. Greenhouse-Gas Fluxes in Baseline Years

Methane and nitrous oxide (CH_4 and N_2O) fluxes in and out of the terrestrial ecosystems were included in the assessment and were modeled using the spreadsheet model. The fluxes of the two gases were converted to carbon dioxide equivalent (denoted as $CO_{2\text{-eq}}$) by using the respective global warming potential (GWP) factors—21 for methane and 310 for nitrous oxide (EPA, 2003). The carbon flux estimates reported in the previous section were converted to carbon dioxide equivalent using a conversion factor of 3.664 and a GWP factor of 1 (EPA, 2003). The average estimated fluxes of the three gases during the baseline years are presented in table 5.6. Note that these flux estimates do not include the aquatic fluxes presented in chapter 10 of this report. The combined flux estimates in a regional carbon budget are presented and discussed in chapter 12 of this report.

Table 5.5. Comparison of estimated average carbon stocks and fluxes in the five ecoregions of the Western United States, by the three simulation models.

[Negative numbers indicate carbon sequestration; positive numbers indicate loss of carbon to the atmosphere. EDCM, Erosion-Deposition-Carbon Model; TgC, teragrams of carbon; TgC/yr, teragrams of carbon per year]

Models		Ecoregions					
		Western Cordillera	Marine West Coast Forest	Cold Deserts	Warm Deserts	Mediterranean California	Western United States
Carbon stock (TgC)	CENTURY	7,867.7	1,474.9	3,055.1	910.3	920.6	14,228.7
	EDCM	8,365.9	1,560.7	2,342.8	529.2	861.3	13,659.8
	Spreadsheet	8,439.0	1,632.7	2,362.6	582.7	762.3	13,779.2
	Model variability (percent)	7	10	28	57	19	4
Carbon flux (TgC/yr)	CENTURY	−85.3	−6.2	−30.1	−18.4	−18.0	−158.0
	EDCM	−24.6	−2.0	1.9	2.7	−13.2	−35.2
	Spreadsheet	−19.7	−2.1	−1.9	−0.2	−2.4	−26.3
	Model variability (percent)	152	121	320	398	139	180

Table 5.6. Minimum and maximum estimated averages of annual carbon dioxide, methane, and nitrous oxide fluxes and their total global warming potential from 2001 to 2005 in the Western United States, by greenhouse-gas type for each ecosystem in each ecoregion.

[Estimates of methane (CH_4) and nitrous oxide (N_2O) were generated by the spreadsheet model. The carbon-dioxide (CO_2) estimate is the average of the EDCM and CENTURY model simulations. Global warming potential is the sum of carbon dioxide, methane, and nitrous oxide; $TgCO_{2\text{-eq}}$/yr, teragrams of carbon dioxide equivalent per year]

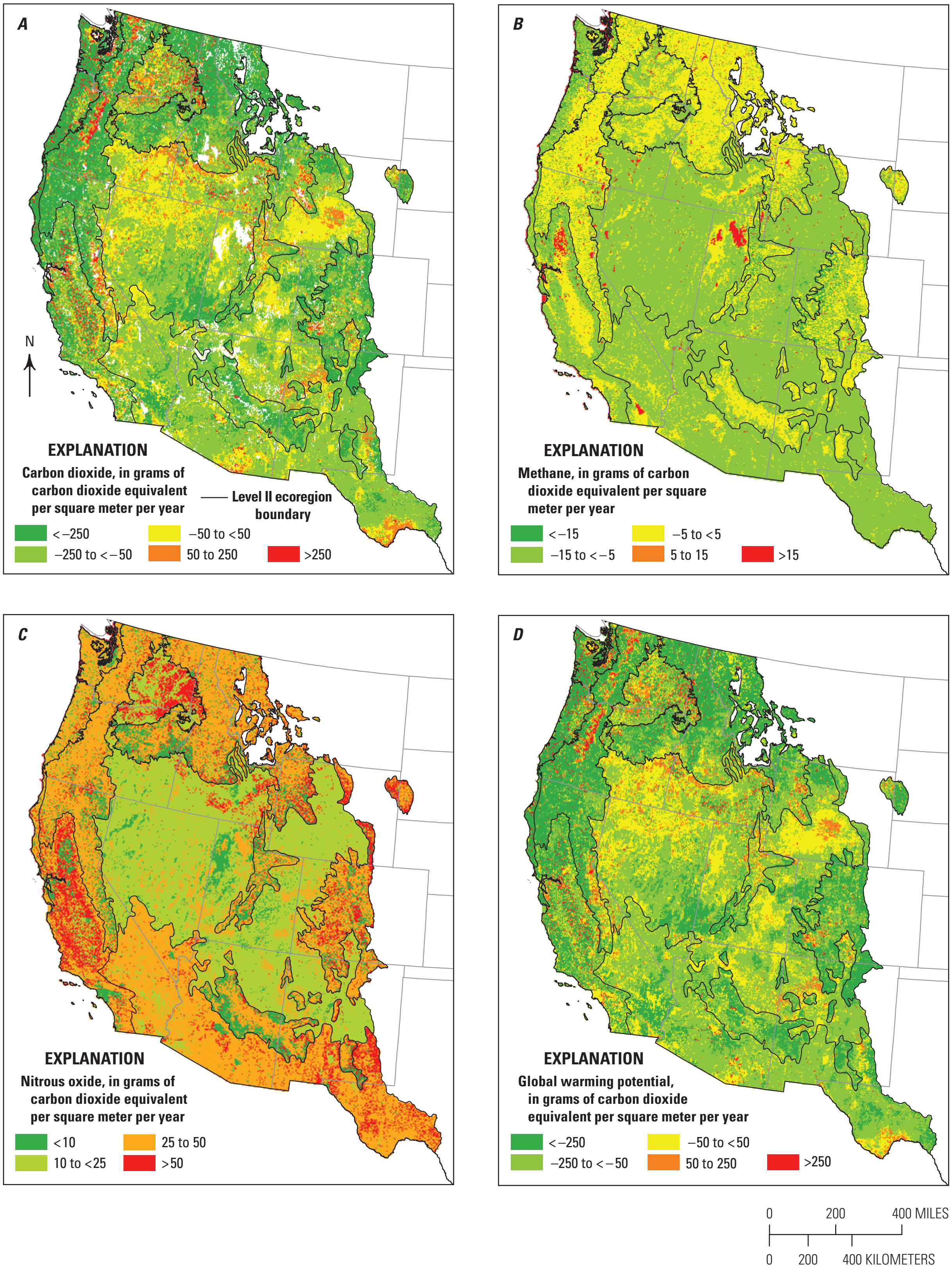
Ecoregion	Ecosystem	Carbon dioxide ($TgCO_{2\text{-eq}}$/yr)		Methane ($TgCO_{2\text{-eq}}$/yr)		Nitrous oxide ($TgCO_{2\text{-eq}}$/yr)		Global warming potential ($TgCO_{2\text{-eq}}$/yr)	
		Min	Max	Min	Max	Min	Max	Min	Max
Western Cordillera	Forests	−257.9	−72.0	−0.9	−0.9	0.3	0.3	−258.5	−72.6
	Grasslands/shrublands	−53.6	0.8	−0.8	−0.8	0.2	0.2	−54.2	0.2
	Agricultural lands	−1.4	0.1	0.0	0.0	0.0	0.0	−1.4	0.1
	Wetlands	−2.7	−0.4	0.4	0.4	0.0	0.0	−2.3	0.0
	Other lands	−0.6	1.6	0.0	0.0	0.0	0.0	−0.6	1.6
	Total	−316.1	−69.9	−1.3	−1.3	0.6	0.6	−316.8	−70.6
Marine West Coast Forest	Forests	−21.9	−4.9	−0.2	−0.2	0.0	0.0	−22.1	−5.1
	Grasslands/shrublands	−2.5	−0.2	0.0	0.0	0.0	0.0	−2.5	−0.2
	Agricultural lands	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.4
	Wetlands	−0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.2
	Other lands	−0.9	0.9	0.4	0.4	0.0	0.0	−0.5	1.3
	Total	−25.3	−3.7	0.3	0.3	0.1	0.1	−24.9	−3.3
Cold Deserts	Forests	−28.6	5.7	−0.4	−0.4	0.1	0.1	−29.0	5.3
	Grasslands/shrublands	−76.6	13.9	−2.8	−2.8	0.2	0.2	−79.2	11.3
	Agricultural lands	−11.2	0.0	−0.1	−0.1	0.1	0.1	−11.1	0.1
	Wetlands	−2.2	0.1	0.8	0.8	0.0	0.0	−1.4	0.9
	Other lands	−0.9	1.3	0.4	0.4	0.0	0.0	−0.5	1.7
	Total	−119.6	21.0	−2.1	−2.0	0.4	0.4	−121.3	19.4
Warm Deserts	Forests	−2.1	0.8	0.0	0.0	0.0	0.0	−2.1	0.8
	Grasslands/shrublands	−59.0	10.0	−1.0	−1.0	0.4	0.4	−59.7	9.4
	Agricultural lands	−6.6	−0.2	0.0	0.0	0.0	0.0	−6.6	−0.2
	Wetlands	−0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.1
	Other lands	−0.4	0.1	0.1	0.1	0.0	0.0	−0.3	0.2
	Total	−68.2	10.8	−0.9	−0.9	0.4	0.4	−68.7	10.3
Mediterranean California	Forests	−22.5	−9.6	−0.1	−0.1	0.0	0.0	−22.6	−9.7
	Grasslands/shrublands	−23.6	1.0	−0.2	−0.2	0.1	0.1	−23.7	0.9
	Agricultural lands	−20.5	0.7	0.8	0.9	0.1	0.1	−19.6	1.7
	Wetlands	−0.5	0.3	0.2	0.2	0.0	0.0	−0.4	0.5
	Other lands	−1.5	−0.5	0.2	0.2	0.0	0.0	−1.3	−0.3
	Total	−68.6	−8.2	0.9	1.0	0.2	0.2	−67.5	−7.0
Western United States (total)	Forests	−333.0	−80.1	−1.7	−1.7	0.4	0.4	−334.2	−81.3
	Grasslands/shrublands	−215.3	25.5	−4.8	−4.8	0.9	0.9	−219.2	21.6
	Agricultural lands	−39.7	0.9	0.7	0.8	0.3	0.3	−38.8	2.0
	Wetlands	−5.5	0.2	1.6	1.6	0.0	0.0	−4.0	1.8
	Other lands	−4.3	3.4	1.1	1.2	0.1	0.1	−3.1	4.6
	Total	−597.7	−50.0	−3.1	−2.9	1.7	1.7	−599.1	−51.3

The data in table 5.6 indicate that the fluxes of methane and nitrous oxide in the ecoregions of the Western United States were generally low. As a whole, the Western United States served as a GHG sink, sequestering GHGs at an estimated average rate of −232.51 $TgCO_{2\text{-eq}}$/yr (ranging from −599.1 to −51.3 $TgCO_{2\text{-eq}}$/yr). The CO_2 sink dominated the contribution (about 99 percent) to the total GWP of the GHGs. The overall GHG sink in the terrestrial ecosystems of the Western United States is equivalent to 4.9 percent of the Nation's total greenhouse gas emissions in 2010, as reported by the EPA's 2012 national greenhouse gas inventory report (EPA, 2012). The average annual nitrous oxide emission rate for the entire Western United States was 1.65 $TgCO_{2\text{-eq}}$/yr, of which the Western Cordillera and Warm Deserts ecoregions contributed 61 percent even though they cover only 50 percent of the land area. The Marine West Coast Forest and Mediterranean California ecoregions acted as methane sources at 0.3 and 0.9 $TgCO_{2\text{-eq}}$/yr, respectively, for the baseline years, whereas other ecoregions acted as methane sinks. The Mediterranean California ecoregion is only 1.8 times larger in area than the Marine West Coast Forest but its methane emissions were 3 times greater because Mediterranean California had more wetlands and agricultural lands, which had higher methane emission rates than other ecosystems (fig. 5.6). Whether an ecoregion was a sink or source of methane was largely associated with the land-cover composition, especially its proportion of wetlands and agricultural lands. Agricultural lands and wetlands tended to emit methane, whereas forests and grasslands/shrublands tended to sequester methane.

On average, all of the ecosystems in the Western United States were carbon dioxide sinks and nitrous-oxide sources; for the baseline years, both forests and grasslands/shrublands were methane sinks, and wetlands were methane sources. The methane budget varied regionally; Mediterranean California was a source (estimated average of 0.82 $TgCO_{2\text{-eq}}$/yr) and the other ecoregions were sinks. The grasslands/shrublands ecosystem in the Cold Deserts and the Western Cordillera consumed methane at −5.9 and −9.4 $gCO_{2\text{-eq}}/m^2$/yr, respectively (fig. 5.6*B*). The wetlands ecosystem for the Western United States emitted the largest amount of methane at an average rate of 105 $gCO_{2\text{-eq}}/m^2$/yr (fig. 5.6*B*). Agricultural lands emitted nitrous oxide at a rate of 97.9 $gCO_{2\text{-eq}}/m^2$/yr in some parts of Mediterranean California, higher than for any of the other ecosystems (fig. 5.6*C*). The spatial distribution of the GWP for each GHG generally coincided with the spatial distribution of the ecosystems (fig. 5.6). A higher carbon dioxide uptake was associated with forested areas (green color in figure 5.6*A*), but higher carbon dioxide emissions were associated with agricultural lands and clearcut areas of forests (red color in figure 5.6*A*). Overall, forests covered 28 percent of the land area of the Western United States (746,343 km^2) but accounted for 64 percent of the GHG flux. On the other hand, grasslands/shrublands covered 59 percent of the area but accounted for only 32 percent of the GHG flux. Agricultural lands covered only 6 percent of the area but emitted 15 percent of nitrous oxide, whereas wetlands covered only 0.4 percent of the area and emitted roughly the same amount of methane (1.6 $TgCO_{2\text{-eq}}$/yr) as all other emitters combined.

5.5. Summary

The total carbon stocks and fluxes in terrestrial ecosystems were estimated using three biogeochemical models on the GEMS platform. The modeling was constrained by the USDA FIA forest inventory data, the USDA NASS grain-yield statistics, and the MODIS NPP product. For carbon stocks in the ecosystems of the entire Western United States in 2005, the biomass and the top 20 cm of the soil layer contained an estimated average of 13,920 TgC (ranging from 12,418 to 15,460 TgC). The Western Cordillera stored the most carbon (59 percent of the total), followed by the Cold Deserts (19 percent), the Marine West Coast Forest (11 percent), the Mediterranean California (6 percent), and the Warm Deserts (5 percent). Forests, grasslands/shrublands, and agricultural lands stored 69 percent, 25 percent, and 4 percent of the total carbon, respectively. As a comparison, the total forest area, the average total forest carbon stock, and the average forest stock density estimated by this assessment for 2005 in the five ecoregions were 74.6 Mha, 9,675 TgC, and 13.0 kgC/m^2, respectively. A separate analysis (Brad Smith, USDA Forest Service, unpub. data, 2010) using the USFS FIA forest area and forest carbon stock estimation methods (Nelson and Vissage, 2005; J.E. Smith and Heath, 2008) suggested a total of 93.6 Mha of forested area, a total forest carbon stock of 13,579 TgC, and an average forest carbon stock density of 14.5 kgC/m^2 for the same five ecoregions. The differences between the two studies may be attributed to two factors: (1) the total forest area used by the two studies was different, and (2) only carbon in the top 20 cm of the soil layer was modeled as SOC in this assessment, compared to the FIA SOC estimate, which used the top 1 m of the soil layer.


A
N
EXPLANATION
Carbon dioxide, in grams of carbon dioxide equivalent per square meter per year
Level II ecoregion boundary
<−250
−50 to <50
−250 to <−50
50 to 250
>250
B
EXPLANATION
Methane, in grams of carbon dioxide equivalent per square meter per year
<−15
−5 to <5
−15 to <−5
5 to 15
>15
C
EXPLANATION
Nitrous oxide, in grams of carbon dioxide equivalent per square meter per year
<10
25 to 50
10 to <25
>50
D
EXPLANATION
Global warming potential, in grams of carbon dioxide equivalent per square meter per year
<−250
−50 to <50
−250 to <−50
50 to 250
>250
0 200 400 MILES
0 200 400 KILOMETERS

The overall average annual net carbon flux in terrestrial ecosystems of the Western United States was estimated to be −86.5 TgC/yr (ranging from −162.9 to −13.6 TgC/yr) from 2001 to 2005. Forests were the largest carbon sink (62 percent of the total), followed by grasslands/shrublands (30 percent) and agricultural lands (7 percent). Of the total carbon sequestered on an annual basis, about one-third was accumulated in live biomass and the rest was allocated to the dead biomass (forest litter and dead, woody debris) and soil carbon pools. For the baseline years of 2001 to 2005, the estimated average annual net carbon flux in forests estimated in this assessment (−54 TgC/yr, ranging from −90.7 to −21.8 TgC/yr) was comparable to an estimate by Heath and others (2011) of −43.1 TgC/yr (ranging from 24.9 to −111.2 TgC/yr) for the years 2000 to 2008. The average annual net carbon flux estimates from the two studies may be expressed as per-unit-of-area carbon flux: −72.4 $gC/m^2/yr$ from this assessment and −93.8 $gC/m^2/yr$ from Heath and others (2011).

A comparison of carbon stock and flux indicates that there are still profound differences and uncertainties within carbon estimation methods, models, and data sources. Further comparisons between models may help to reveal the major causes of those differences, such as model structure, parameter sensitivity, and data assimilation.

Figure 5.6. (see facing page). Maps showing the spatial distribution of the average annual carbon dioxide, methane, and nitrous oxide fluxes and their total global warming potential from 2001 to 2005 in the Western United States. The flux of carbon dioxide is an average of estimates derived from the spreadsheet model, CENTURY model, and the EDCM in the General Ensemble Modeling System (GEMS). The fluxes of methane and nitrous oxide were derived from the spreadsheet model alone in the GEMS. *A*, Carbon dioxide. *B*, Methane. *C*, Nitrous oxide. *D*, Global warming potential. EDCM, Erosion-Deposition-Carbon Model. See figure 1.1 in chapter 1 for ecoregion names.

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