

# **An Assessment of Carbon Sequestration in Ecosystems of the Western United States—Scope, Methodology, and Geography**

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Chapter 1 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 1. An Assessment of Carbon Sequestration in Ecosystems of the Western United States—Scope, Methodology, and Geography

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## 1.1. Scope and General Methodology of the Assessment

This is the second in a series of reports produced by the USGS for a national assessment of carbon sequestration and greenhouse-gas (GHG) fluxes in ecosystems. The first report (Zhu and others, 2011) covered ecosystems of the Great Plains region of the United States. This report covers ecosystems in the Western United States, which extends from the Rocky Mountains in the east to the Pacific coastal waters in the west. The area of coverage is approximately 2.66 million square kilometers (fig. 1.1).

The carbon sequestration and GHG flux assessment was mandated by the Energy Independence and Security Act of 2007 (EISA; U.S. Congress, 2007), which directed the U.S. Department of the Interior to produce a methodology and conduct a national assessment to quantify (1) the amount of carbon stored in ecosystems, (2) the capacity of ecosystems to sequester carbon, and (3) the rate of GHG fluxes in and out of the ecosystems. This regional assessment has two major objectives: (1) implement the EISA mandate to conduct a national assessment of carbon sequestration and GHG fluxes, and (2) improve the understanding of the regional carbon cycling by focusing on changes in carbon stocks and fluxes in all the major ecosystems, and on the major natural and anthropogenic processes that control carbon cycling (such as climate change, land use, and wildland fires). The GHGs considered in this assessment were carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO, from wildland fires only), dissolved inorganic carbon (DIC), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O).

The major ecosystems evaluated in this study are both terrestrial (forests, wetlands, grasslands/shrublands, and agricultural lands) and aquatic (rivers, lakes, estuaries, and coastal waters). The thematic definitions of the ecosystems and their spatial boundaries are outlined in table 2.1 of chapter 2 of this report and in Zhu and others (2010). The definitions are largely based on the National Land Cover Database (NLCD; Vogelmann and others, 2001; Homer and others, 2007), which was the primary source of initial land-use and land-cover (LULC) data for this assessment. The LULC data derived from remote sensing datasets were used to define the spatial boundaries of the ecosystems that were assessed in this study; because the remote-sensing data allowed for wall-to-wall coverage of the Western United States, the resulting spatially and temporally explicit data products and estimates are considered to be comprehensive.

Within the NLCD database, both land use (for example, agricultural lands) and land cover (for example, forests) are mapped using data acquired from Landsat satellites. Within the LULC classes, land-management activities were defined as those actions that were aligned with the LULC classes and modified the way land was used, but did not change the LULC classes; for instance, cropland irrigation or fertilization was a land-management activity that did not change the LULC class of the land. Ecosystem disturbances were defined as those natural disturbances that altered the production of carbon or other functions in an ecosystem. For this assessment, wildland fire was the only natural disturbance that was considered.

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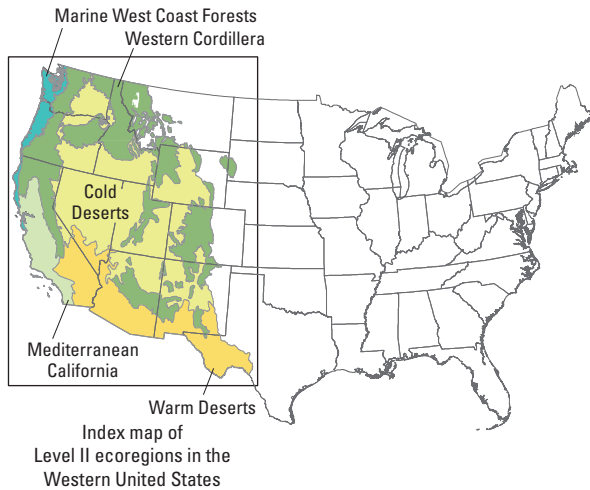
<sup>2</sup>U.S. Geological Survey, Menlo Park, Calif.

<sup>3</sup>U.S. Geological Survey, Denver, Colo.




















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





**EXPLANATION**

<b>Land cover</b>		<b>Western Cordillera</b>	
	Water	<b>C</b>	Cascades
	Developed	<b>NC</b>	North Cascades
	Mechanically disturbed (national forest)	<b>ECSF</b>	East Cascades— Slopes and Foothills
	Mechanically disturbed (other public protected)	<b>KM</b>	Klamath Mountains
	Mechanically disturbed (private land)	<b>BM</b>	Blue Mountains
	Mining	<b>SNM</b>	Sierra Nevada Mountains
	Barren	<b>NR</b>	Northern Rockies
	Deciduous forest	<b>CR</b>	Canadian Rockies
	Evergreen forest	<b>WUM</b>	Wasatch-Uinta Mountains
	Mixed forest	<b>MR</b>	Middle Rockies
	Grassland	<b>SR</b>	Southern Rockies
	Shrubland	<b>ANM</b>	Arizona-New Mexico Mountains
	Agriculture	<b>Marine West Coast Forest</b>	
	Hay/pasture	<b>CR</b>	Coast Range
	Herbaceous wetland	<b>PL</b>	Puget Lowland
	Woody wetland	<b>WV</b>	Willamette Valley
	Ice/snow	<b>Cold Deserts</b>	
<b>Ecoregion boundary</b>		<b>CP</b>	Columbia Plateau
	Level III	<b>SRP</b>	Snake River Plain
	Level II	<b>NBR</b>	Northern Basin and Range
		<b>CBR</b>	Central Basin and Range
		<b>WB</b>	Wyoming Basin
		<b>CP</b>	Colorado Plateaus
		<b>ANP</b>	Arizona-New Mexico Plateau
		<b>Warm Deserts</b>	
		<b>MBR</b>	Mojave Basin and Range
		<b>SBR</b>	Sonoran Basin and Range
		<b>MA</b>	Madrean Archipelago
		<b>CD</b>	Chihuahuan Deserts
		<b>Mediterranean California</b>	
		<b>CCV</b>	Central California Valley
		<b>SCM</b>	Southern California Mountains
		<b>SCCOW</b>	Southern and Central California Chaparral and Oak Woodlands

**Figure 1.1 (see facing page).** Map showing the spatial extent of this assessment. The Western United States region consists of five level II ecoregions (modified from U.S. Environmental Protection Agency, 1999); they are the Marine West Coast Forest, Western Cordillera, Cold Deserts, Warm Deserts, and Mediterranean California. The level III ecoregions also are shown. The total area of the Western United States is approximately 2.66 million square kilometers. The land-use and land-cover classes shown on the map represent conditions that existed around 2005.

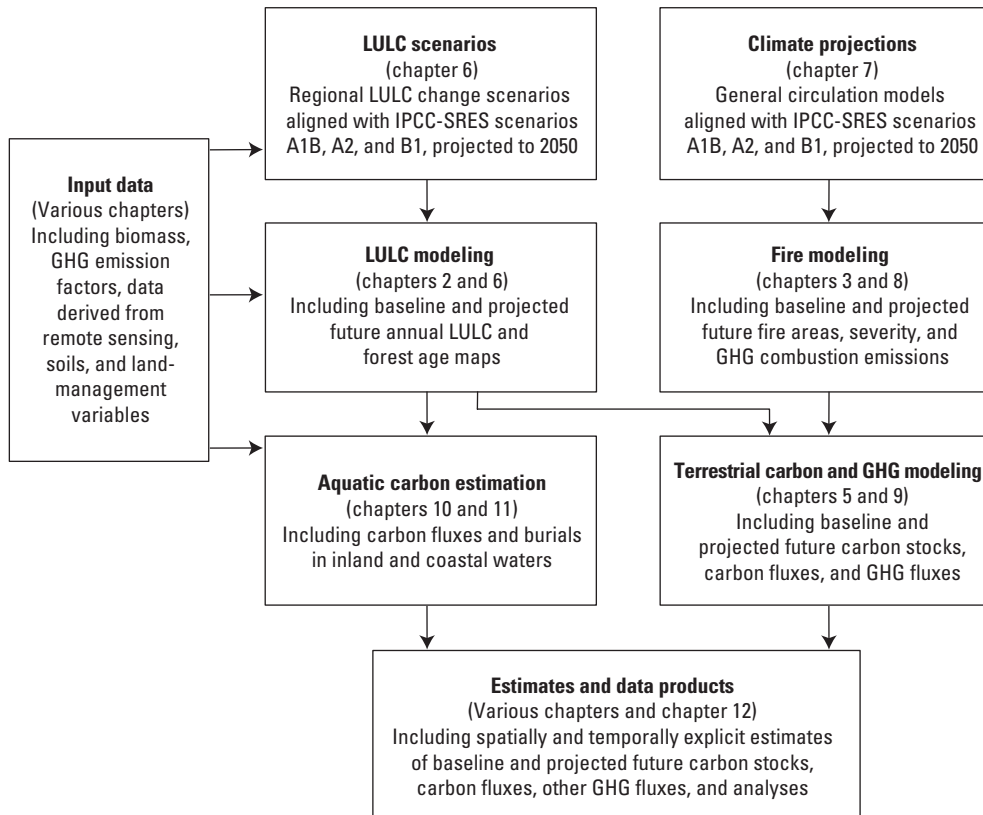


#### 4 Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of the Western United States

The assessment was conducted using a methodology framework that (1) linked land use, land management, and climate data with statistical and process-based methods and models to generate spatially and temporally explicit carbon storage and GHG flux estimates; (2) used remote sensing input data, existing resource and soil inventories, climate histories, and measurements made by a national network of streamgages; and (3) applied a set of future land- and climate-change scenarios to the assessment to estimate a range of carbon stocks and sequestration rates in ecosystems. The major components of the assessment methodology and their connections are shown in figure 1.2, with corresponding chapters of this report marked in the boxes and methodological details described in the chapters.

The methodology framework shown in figure 1.2 is both spatially and temporally explicit. The spatial foundation of the assessment is the LULC modeling component (chapter 2), in which the ecosystems were mapped seamlessly, and all pixels were partitioned into LULC and LULC-change classes. The temporal foundation of the assessment was twofold and

included baseline data (currently available data for various controlling variables) and future projected data (generated by the use of scenarios; chapter 6). Both the baseline and future projected data (from contemporary time to 2050) were collected in a manner consistent with the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (Nakicenovic and others, 2000). The area burned by, severity of, and emissions from wildland fires during both the baseline and future projection periods were estimated by integrating remote sensing data with statistical and landscape modeling (chapters 3 and 8). The baseline and future projected terrestrial ecosystems' carbon stocks and fluxes were estimated by using process-based models, which took into account various biomass and soil-carbon input data as well as the results of LULC and wildland-fire modeling (chapters 5 and 9). Estimates of baseline carbon flux and sequestration in both inland and coastal aquatic ecosystems were calculated separately and were based on a series of studies detailed in chapters 10 and 11. General circulation models of future climate-change projections (described in chapter 7) were



**Figure 1.2.** Flow diagram showing the general methodology framework. The heading in each box represents a major component of the assessment. The chapter numbers indicate where in this report those components are discussed. Arrows

show relations between components. GHG, greenhouse gas; IPCC-SRES, Intergovernmental Panel of Climate Change Special Report on Emissions Scenarios (Nakicenovic and others, 2000); LULC, land use and land cover.



incorporated into the assessment to allow for an analysis of the effects of future climate change. The relation between the estimates of carbon sequestration and flux and natural and anthropogenic processes is briefly presented in chapter 12.

Both current and projected future changes in carbon storage and GHG fluxes were estimated in the assessment in order to establish a baseline and provide a range of potential carbon-sequestration capacities, which is a requirement of the EISA. The term “baseline” is defined as the average contemporary annual conditions to be assessed. Different components of the assessment have different ranges of baseline years because they are limited by the years for which data were available, as follows: LULC (1992–2005), wildland fires (2001–2008), terrestrial carbon and GHG fluxes (2001–2005), and aquatic carbon fluxes (1920s to present). The input datasets used for the assessment include those developed by the USGS and other agencies and organizations. The output datasets are in the form of either annual digital maps or annual statistics. The digital maps have a nominal spatial resolution of 250 by 250 meters. Because the assessment was conducted at both national and broad regional scales, the resulting information and data products should be applied only at the regional scale or broader.

The methodology was developed to meet the above-noted objectives, particularly to analyze the carbon dynamics in relation to land use, land management, and climate changes. This assessment did not include a GHG life-cycle analysis or an economic feasibility modeling of land use changes. In addition, vegetation dynamics from succession or climate change were not modeled for the assessment, and the major components of the assessment were not coupled in a completely integrative modeling system (such a modeling system is not yet available for such a comprehensive assessment). The justification of the methodology, design rationales, and technical specifications are detailed in Zhu and others (2010) and are therefore not repeated in this report.

This assessment is organized by five level II ecological regions (ecoregions), which were adapted from the U.S. Environmental Protection Agency ecoregion map (EPA, 1999): (1) Western Cordillera, (2) Marine West Coast Forest, (3) Cold Deserts, (4) Warm Deserts, and (5) Mediterranean California (fig. 1.1). All of the assessment models were parameterized and the results were calibrated and validated on the basis of these ecoregions. In this report, the term “region” is often used in a general sense, depending on the context, whereas the term “ecoregion” refers to the EPA ecoregion hierarchy (EPA, 1999). The major terrestrial and aquatic ecosystems are analyzed within these ecoregions. The use of the ecoregions and the NLCD’s LULC classes chosen for the ecosystems in this assessment suggests that the reported results are meaningful within the defined ecoregion and

ecosystem boundaries and may not be directly comparable with other national-level or regional estimates because of the different boundary definitions. Further discussion of the ecoregions and ecosystems may be found in Zhu and others (2010).

The term “flux” refers both to emissions of GHG (such as carbon) to the atmosphere and to uptake by ecosystems. In presenting the results of terrestrial carbon flux assessment, the terms “net flux” and “net ecosystem carbon balance” (NECB) are also used interchangeably in the report to refer to the net rate of the change in carbon storage in ecosystems. The terms used in calculating NECB and (or) net flux include “net ecosystem production” (NEP, which is the difference between the net primary production and the heterotrophic respiration), “long-term fire emissions,” and “biomass harvesting.” When reporting losses or gains in carbon storage, a negative number indicates carbon uptake, carbon sequestration, or a carbon sink; a positive number indicates a carbon emission or a carbon source. These conventions are used throughout the report unless noted. The usages follow standard conventions found in the literature on this topic (such as Chapin and others, 2006; EPA, 2012) and are consistent with the terms used in the assessment report for the Great Plains region (Zhu and others, 2011).

In addition to assessing carbon storage and fluxes in ecosystems, the fluxes or emissions of other GHGs (such as CO<sub>2</sub>, CH<sub>4</sub>, CO, DIC, and N<sub>2</sub>O) were also assessed. Fluxes or emissions of the other GHGs are reported as carbon dioxide equivalent (CO<sub>2</sub>-eq) values and flux estimates were calculated on the basis of their respective global warming potential factors.

The units of measurement used in this report also follow previous usages. The total amount of carbon for a given region is reported in teragrams of carbon (TgC). When reporting carbon stock per unit of area, the values are given in kilograms of carbon (kgC). When reporting the carbon flux per unit of area, the values are given in grams of carbon (gC).

Whenever possible, the estimates are provided as a range of values in order to represent the spread of variability in assessment results. The ranges of values were derived on the following basis: (1) the range of baseline values was derived from the minimum and maximum of averages of model runs over the years 2001 to 2005, and (2) the range of projected future values was derived from the means of the unique LULC scenarios, climate-change projections, and biogeochemical models over projection years (2006–2050). The same calculations were applied to the baseline and future potential components of the wildland-fire assessment (chapters 3 and 8). For the aquatic ecosystem assessment (chapter 10), the range of values was derived from the 5th and 95th confidence intervals of Monte Carlo simulations.

## 1.2. Regional Geography

The five level II ecoregions covered by this assessment include the Western Cordillera, the Marine West Coast Forest, the Cold Deserts, the Warm Deserts, and Mediterranean California. The five ecoregions can be grouped into two large areas: (1) the Western Cordillera and Marine West Coast Forest, and (2) the Cold Deserts, Warm Deserts, and Mediterranean California. The following sections summarize the climate, physiography, hydrology, vegetation, and land use in these groupings of ecoregions. This geographic characterization provides a foundation for understanding the differences in carbon sequestration and fluxes between ecoregions in the Western United States.

### 1.2.1. The Western Cordillera and Marine West Coast Forest

The maritime and inland mountains and forests of the Western United States generally coincide with the Western Cordillera and Marine West Coast Forest (fig. 1.2). The mountainous areas of the Pacific Coast States include the Coast Range, the Cascades (including the North Cascades and the East Cascades—Slopes and Foothills), the Klamath Mountains, and the Sierra Nevada Mountains. Inland, the mountainous areas include the Rocky Mountains (Canadian Rockies, Northern Rockies, Middle Rockies (including the Black Hills), and Southern Rockies), Blue Mountains, Wasatch-Uinta Mountains, and the Arizona-New Mexico Mountains. These ecoregions contain some of the country's wettest climates (coastal temperate rain forests) and extremely cold climates (high alpine peaks), as well as semiarid and arid areas at low elevations, especially in the southern portions of the area. Although this area is mostly forested in comparison to the surrounding ecoregions, grasslands/shrublands also cover some parts of it. Forestry, mining, livestock grazing, wildlife habitat, tourism, and recreation are major land uses, along with some cropland and pasture in the larger valleys.

The Western United States is generally more arid than the rest of the country. Because of the topographic effect of the mountains, however, precipitation and runoff amounts in these two ecoregions are higher than in the adjacent ecoregions in the Great Plains, Basin and Range, and deserts. As much as 80 percent of the runoff is snowmelt (Stewart and others, 2004) and runoff distinctly increases with elevation, contributing to the headwaters of major rivers such as the Columbia and Colorado Rivers. A large portion of runoff originates in a relatively small fraction of the area compared to the Eastern United States, where runoff is relatively and spatially more uniform (Lettenmaier and others, 2008). Another distinct hydrologic feature is the Great Basin, a large endorheic (closed) basin that is disconnected from

any coastal outlet. Therefore, any water that falls as rain or snow into this region does not escape out of it; surface water either evaporates or percolates instead of flowing toward the ocean (Orme, 2002).

The Western Cordillera ecoregion is a region of high, rugged, mostly forested mountains with a few open valleys. Plants, animals, and land use vary greatly with elevation. The lower elevations are commonly covered by grasslands/shrublands, the middle elevations are mostly forested, and most of the higher alpine areas above the timberline are covered with snow and ice for much of the year. Coniferous forests vary by latitude, elevation, and proximity to maritime influence but are primarily dominated by species such as Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), subalpine fir (*Abies lasiocarpa*), grand fir (*A. grandis*), Engelmann spruce (*Picea engelmannii*), whitebark pine (*Pinus albicaulis*), lodgepole pine (*P. contorta*), ponderosa pine (*P. ponderosa*), and quaking aspen (*Populus tremuloides*).

Numerous small- to medium-sized streams and rivers and many small, naturally formed mountain lakes are found at high elevations (Melack and others, 1997; EPA, 2009). Caldera lakes, such as Crater Lake in Oregon and Yellowstone Lake in Wyoming, are located in the ecoregion (EPA, 2009). Several large rivers, such as the Columbia, Snake, Missouri, and Colorado River, have their headwaters in this region; downstream, these rivers are totally or partially regulated (Benke and Cushing, 2005). Grazing, which is the leading land use in the valleys and lower elevations of the Western Cordillera, has had a major impact on the quality of lands and streams. Timber harvesting is an important land use in the more heavily forested lower and middle elevations. Mining activities cover relatively small but numerous areas. Wildland fires are common and can burn extensive areas during drought years, especially when preceded by moist years with high vegetation productivity (Swetnam and Betancourt, 1990; Westerling and others, 2006; Littell and others, 2009). Large areas of the region are Federally managed public lands.

The Marine West Coast Forest ecoregion is characterized by a cool, moist climate with dry summers and wet, generally snowless winters. The low mountains of the Coast Range are covered by highly productive, rain-drenched needleleaf evergreen forests. The high levels of precipitation contribute to the magnitude of the streamflow found in many of the large rivers of the ecoregion, particularly the Columbia River. The Columbia, Umpqua, Rogue, Klamath, and Sacramento Rivers have their headwaters in the Western Cordillera and run through the maritime forests before draining to the Pacific Ocean. Sitka spruce (*Picea sitchensis*) forests originally dominated the fog-shrouded coast, and a mosaic of western red cedar, western hemlock, and seral Douglas-fir blanketed the inland areas. Wildland fires are rare, largely because of the moisture regime of this ecoregion; however, wildland fires

can be severe and extensive when they do occur (Agee, 1993; Littell and others, 2009). Today, Douglas-fir plantations are prevalent on the intensively logged and managed landscape and play a major role in producing forest carbon stocks. In California, redwood (*Sequoia sempervirens*) forests, which represent one of the largest carbon stocks in the country, are a dominant component of the region, along with some hardwoods such as tanoak (*Lithocarpus densiflorus*), Pacific madrone (*Arbutus menziessi*), bigleaf maple (*Acer macrophyllum*), and red alder (*Alnus rubra*). This ecoregion includes the drier, flatter, and more populated Willamette Valley and Puget Lowland, which are in the rain shadow of the Coast Range and Olympic Mountains. The fertile soil and temperate climate make the Willamette Valley an extremely productive agricultural area.

### 1.2.2. Cold Deserts, Warm Deserts, and Mediterranean California

The Cold Deserts, Warm Deserts, and Mediterranean California ecoregions stretch from Canada to Mexico and from the Pacific to the Great Plains, covering portions of 11 Western States. They are distinguished from the adjacent Western Cordillera and Marine West Coast Forest ecoregions by their aridity; mostly shrub, grass, and desert scrub vegetation; and generally lower relief and elevations. The dominant landforms include plains with hills and low mountains, plateaus and high-relief tablelands, some high mountains, and intermountain basins and valleys. The climate of the deserts is generally dry and Mediterranean California has a milder Mediterranean (hot summer and mild, wet winter) climate. Because of the climate, the hydrology of the ecoregions is different than that of the Western Cordillera and Marine West Coast Forest ecoregions. The annual precipitation in these ecoregions is highly variable and extreme droughts are not uncommon. Most streams and small rivers in these ecoregions are ephemeral, and the few perennial rivers originate in the adjacent forested mountainous ecoregions. A high proportion of the region is Federally managed public land, and the hydrology of many of the larger rivers has been greatly modified by dams, irrigation projects, and groundwater and surface-water extraction. The dry conditions and water withdrawals have caused some internal drainages to end in saline lakes (such as Utah's Great Salt Lake) or desert basins without reaching the ocean.

The Cold Deserts ecoregion is arid and includes a variety of physiographic features, such as basin-and-range terrain (a series of alternating linear valleys and mountain ranges), broad plateaus, and other mountains ranges and valleys. The ecoregion includes the Columbia Plateau and Snake River Plain (both of volcanic origin), the northern and central Great Basin, the Wyoming Basin, and the Colorado Plateau. The ecoregion is almost completely surrounded by the wetter,

higher, more rugged, and forested mountain ranges of the Western Cordillera ecoregion. These wetter regions feed some of the headwaters and upper reaches of smaller rivers such as the Humboldt, Bear, Truckee, and Sevier Rivers. Vegetation is sparse and typically dominated by cold-temperate species such as sagebrush (*Artemisia* spp.), various bunchgrasses, and saltbush (*Atriplex* spp.); in the southern part of the ecoregion, there is more blackbrush (*Coleogyne ramosissima*), winterfat (*Krascheninnikovia lanata*), and greasewood (*Sarcobatus vermiculatus*). Juniper (*Juniperus* spp.), pinyon pine (*Pinus edulis*), and singleleaf pinyon (*P. monophylla*) grow in the mountains, along with other conifers at higher elevations. Some areas are barren. Wildland fires are common and their occurrence is strongly related to climate, vegetation productivity, and the presence of invasive species such as cheatgrass (*Bromus tectorum*) (D'Antonio and Vitousek, 1992; Brooks and others, 2004; Mensing and others, 2006). Most of the ecoregion is used as rangeland. There are agricultural lands where irrigation is possible, either by groundwater or by diverting water from the Snake and Columbia Rivers, which flow through the region. Lakes formed by mainstem impoundments are common, including Lake Powell (the reservoir formed by Glen Canyon Dam on the Colorado River) and Franklin D. Roosevelt Lake (formed by the Grand Coulee Dam on the Columbia River).

The Warm Deserts ecoregion includes the Mojave, Sonoran, and Chihuahuan Deserts of the southwestern United States. Most of the ecoregion consists of basin-and-range terrain, where typically north-to-south-trending mountains are separated by broad basins and valleys bordered by sloping alluvial fans. As the name implies, this ecoregion is warmer than the Cold Deserts to the north, and large parts of the ecoregion are drier and at lower elevations. Winter snow is rare. Compared to the Cold Deserts, a larger percentage of the annual precipitation in this more subtropical desert ecoregion falls during the summer months and contributes to the rich diversity of plants and animals. This ecoregion encompasses the middle and lower sections of the Colorado and Rio Grande Rivers, which drain southward to the Gulf of California and the Gulf of Mexico, respectively. In many areas of the Mojave and western and central Sonoran Deserts, desert scrub commonly consists of creosote bush (*Larrea tridentata*) and white bursage (*Ambrosia dumosa*). In the eastern Sonoran Desert, the palo verde (*Cercidium* spp.)-cacti-mixed scrub vegetation includes the saguaro (*Carnegiea gigantea*). Farther to the east, the high Chihuahuan Desert includes some desert grassland and large areas of arid shrubland dominated by creosote bush. The higher mountains in the ecoregion are forested by oak (*Quercus* spp.), juniper, and pinyon woodlands. Historically, wildland fires have been rare in the Warm Deserts, but the presence of invasive species has led to an increase in wildland-fire occurrence (D'Antonio and Vitousek, 1992; Brooks and others, 2004; Brooks and



Chambers, 2011). Large parts of the Warm Deserts ecoregion are Federally owned, and many large lakes in the southwestern canyon regions are the products of large dam construction projects (EPA, 2009). The largest reservoir in the United States, Lake Mead (which was formed by the construction of the Hoover Dam), is located in this ecoregion. Water levels in reservoirs throughout this ecoregion can vary greatly because of drought and large-scale water removal for municipal and agricultural uses.

The Mediterranean California ecoregion is distinguished by a warm, mild Mediterranean climate, shrubland vegetation consisting of chaparral mixed with areas of grassland and oak savanna, agriculturally productive valleys, and a high population (over 30 million people) in extensive urban agglomerations. The vegetation on the chaparral-covered hills includes ceanothus (*Ceanothus* spp.), California buckeye (*Aesculus californica*), manzanita (*Arctostaphylos* spp.), scrub oak (*Quercus* spp.), and mountain-mahogany (*Cercocarpus* spp.). Coast live oak (*Quercus agrifolia*), canyon live oak (*Q. chrysolepis*), Pacific poison oak (*Toxicodendron diversilobum*), and California black walnut (*Juglans californica*) also grow in this ecoregion. The coastal sage scrub consists of chamise (*Adenostoma fasciculatum*), red shank (*A. sparsifolium*), white sage (*Salvia apiana*), black sage (*Salvia mellifera*), buckwheat (*Eriogonum fasciculatum*), golden-yarrow (*Eriophyllum confertifolium*), and coastal cholla (*Cylindropuntia prolifera*). Wildland fires occur frequently in Mediterranean California. Although wildland fires are driven by climate in the arid parts of the Western United States, human influences, invasive species, and extreme winds are particularly important drivers in the Mediterranean California ecoregion (Keeley, 2006; Syphard and others, 2007; Moritz and others, 2010). Most of the larger perennial streams in the ecoregion originate in the bordering higher, wetter, mountainous ecoregions. Although the ecoregion is centered on the broad San Joaquin and Sacramento Valleys, it also contains several low coastal mountain ranges and, in the south, some higher mountain ranges, all of which are of sufficient elevation to contain perennial streams. The bigger rivers in the area—the Sacramento, San Joaquin, and Salinas Rivers—all drain to the Pacific Ocean. The widespread and diversified agriculture with many high-value crops and supporting hydrological engineering have greatly altered the ecosystems that occupy this ecoregion. Urban, suburban, and industrial land uses are significant drivers of land-cover change in some parts of the ecoregion. The central foothills and some of the coastal ranges are livestock grazing areas.

The river discharge into the Pacific coastal waters is dominated by small mountainous rivers. These small mountainous rivers tend to be short, drain watershed areas with high relief, and typically have river mouths discharging near the coast rather than into an estuary (Milliman and Syvitski, 1992; Wheatcroft and others, 2010). The result is that the Pacific coastal waters receive disproportionately large sediment loads compared to the other regions, which

bury carbon directly or help transport it into the deep ocean (Hedges and Keil, 1995). The two largest rivers in the west, the Columbia and Sacramento Rivers, both drain areas of intensive agriculture and carry elevated nutrient loads to coastal waters, leading to an elevated carbon uptake by phytoplankton. Another important physiographic attribute is the shape of the Pacific Ocean basin, which allows the California Current to supply nutrients very close to the coast, which also contributes to phytoplankton production and—because of the high influx of sediment—the sequestration of carbon in coastal waters (Cotrim Da Cunha and others, 2007; Aufdenkampe and others, 2011). Finally, the presence of a narrow continental shelf results in the transport of a large proportion of sediment- and phytoplankton-derived carbon into the deep ocean, where it is effectively sequestered from the atmosphere (Hedges and Keil, 1995).

### 1.3. National and Regional Studies of Carbon Stock and Greenhouse-Gas Fluxes in Ecosystems

Existing estimates of carbon storage, sequestration, and GHG fluxes varied widely by ecosystem and by region in the Western United States. Forests occupy significant land areas and are the most important carbon sink. The forest inventories that were conducted by the U.S. Department of Agriculture (USDA) Forest Service indicated that in 2005, the forests in the Pacific Coast and Rocky Mountain regions (Forest Service regions 1 through 6), regardless of ownership, had a combined carbon stock of 15,095 teragrams of carbon (TgC) (15.7 kilograms of carbon per square meter, or kgC/m<sup>2</sup>); the carbon stock in forests managed by the Forest Service was 8,278 TgC (18.0 kgC/m<sup>2</sup>) (J.E. Smith and Heath, 2008; Heath and others, 2011).

Among the major forest carbon pools in the Western United States, live biomass represented approximately 50 percent of the total carbon stock, with the remaining carbon stock approximately evenly divided between soil organic carbon and dead woody debris (Donnegan and others, 2008; USDA, 2011). Furthermore, forests in the region sequestered carbon at an approximate rate of 87 teragrams of carbon per year (TgC/yr), or 90.85 grams of carbon per square meter per year (gC/m<sup>2</sup>/yr) (excluding the soil organic carbon pool) (J.E. Smith and Heath, 2008). In a separate analysis of recent forest inventories, the carbon stock in western forests was calculated for the five ecoregions used for this assessment (Brad Smith, USDA Forest Service, unpub. data, 2010; USDA Forest Service, 2012b). The results of the analysis showed that, among the five ecoregions and for all the major carbon pools, the Western Cordillera ecoregion contained the most stored carbon in forests and the Marine West Coast Forest had the largest carbon stock per unit of area in forests (table 1.1).

**Table 1.1.** Total and per-unit-of-area carbon stock from all of the major pools in the forest ecosystems in the five ecoregions of the Western United States.

[Data were derived from recent USDA Forest Service inventories and provided by Brad Smith (USDA Forest Service, unpub. data, 2010). Ecoregions are modified from EPA (1999). EPA, Environmental Protection Agency; kgC/m<sup>2</sup>, kilograms of carbon per square meter; TgC, teragrams of carbon]

Modified level II EPA ecoregion	Carbon stock (TgC)	Carbon stock per unit of area (kgC/m <sup>2</sup> )
Western Cordillera	9,878.0	15.9
Marine West Coast Forest	1,809.5	29.6
Cold Deserts	1,248.8	7.0
Warm Deserts	291.5	6.7
Mediterranean California	351.4	11.4
Western United States (total)	13,579.2	14.5

The most recent national GHG inventory report covering the conterminous United States suggested a net flux of  $-293.1$  TgC in 2010 by forests, grasslands, agricultural lands, and settled areas, which represented an offset of approximately 15.4 percent of the total carbon dioxide emissions in the United States (EPA, 2012). Although the national inventory did not differentiate between regions, the net carbon flux per unit of area may be derived for three main categories that were similar to the ecosystem categories used for this assessment: forestlands remaining as forestlands, croplands (which include both row crops and hay and pasture and are similar to the agricultural lands ecosystem of this assessment) remaining as croplands, and grasslands (which include both shrublands and grasslands and are similar to the grasslands/shrublands ecosystem of this assessment) remaining as grasslands. From 2005 to 2010 for the conterminous United States, the derived mean net carbon flux rate per unit of area was  $-96.75$ ,  $-3.42$ , and  $-0.97$  gC/m<sup>2</sup>/yr, respectively, for the above three categories. Using similar input data, Hayes and others (2012) separately determined that from 2000 to 2006, the average annual net fluxes for forests and croplands in the United States were  $-244.4$  and  $-264.3$  TgC/yr, respectively.

Using forest inventory data collected from 2000 to 2008 and covering the six USDA Forest Service regions (regions 1 through 6) in the Western United States (from the Pacific Coast to the Rocky Mountains), Heath and others (2011) estimated that net annual average carbon flux from forested land ranged from 24.9 to  $-111.2$  TgC/yr (mean value of  $-43.1$  TgC/yr, or  $-93.8$  gC/m<sup>2</sup>/yr). The annual carbon sink in the Western United States' forested land was from publicly owned forests; privately owned forests were a minor source (Heath and others, 2011). In a separate study for the State of Oregon, where climate and other biophysical conditions are favorable

for carbon sequestration (particularly in the Marine West Coast Forest part of the State), D.P. Turner, Gockede, and others (2011) used forest-inventory data, land-use maps, and a process-based model to obtain estimates of per-unit-of-area net ecosystem production (NEP) for 2007 (a year with near-average climate conditions). The estimates were  $-101$ ,  $-143$ ,  $-88$ ,  $18$ , and  $-7$  gC/m<sup>2</sup>/yr, respectively, for forests, agricultural lands, woodlands, grasslands, and shrublands ecosystems.

Carbon sequestration is a function of the biogeochemical exchange between plants and the atmosphere, and it is strongly influenced by key controlling processes such as land use, land-management activities, ecosystem disturbances, and climate (Bachelet and others, 2003; Law and others, 2004; Running, 2008). Because water availability is the most limiting factor in the Western United States, carbon production in ecosystems tends to follow a precipitation gradient from west to east (Derner and Schuman, 2007). As a result, there is a high degree of year-to-year variation driven by the availability of moisture and the frequency or severity of related ecosystem disturbances, such as wildland fires. In a study comparing a year with normal average precipitation with a drought year, it was found that drought can reduce the NEP in forests of the Pacific Northwest by as much as 81 percent (D.P. Turner, Gockede, and others, 2011). On the other hand, simulation studies (such as Hudiburg and others, 2009; Smithwick and others, 2009) indicated that, under future climate-change scenarios with more precipitation and higher temperatures, increases in both carbon storage and the rate of sequestration may be expected.

Recent studies have documented an increase in wildland-fire activity in the Western United States as a result of climate change (Swetnam and Betancourt, 1990; Gedalof and others, 2005; Westerling and others, 2006; Littell and others, 2009). The impact of wildland fires on carbon sequestration in ecosystems included both (1) the immediate release of GHGs from combustion emissions and (2) the long-term combined effects of decomposing biomass, which releases carbon into the atmosphere, and regenerating vegetation, which increased the uptake of carbon (Law and others, 2004; Hurteau and Brooks, 2011; D.P. Turner, Ritts, and others, 2011). Although the short-term combustion emissions may be estimated relatively accurately by using remote-sensing data and emission models (van der Werf and others, 2010; French and others, 2011; chapter 3 of this report), other studies have shown that emissions from decomposition over the long term (years and decades) can be higher but more uncertain because burned landscapes may require years or decades for their NEP to return to pre-fire levels (Kashian and others, 2006; Cleary and others, 2010; Hurteau and Brooks, 2011; Kashian and others, in press). If the increases in fire frequency since 2000 in the Western United States continue into the future, the effects on carbon sequestration in ecosystems can be profound and need to be properly accounted for.

Various land-use policies and land-management actions in the Western United States have been implemented over the last 30 years to adapt to the changing climate and to the societal needs for ecosystem services. For example, since the 1980s in the Pacific Northwest, a decline in forest clearcutting, which was the result of changes in forest-management policies, has led to an increased per-unit-of-area net flux of carbon: from 48 gC/m<sup>2</sup>/yr (a source) in the 1980s to -141 and -136 gC/m<sup>2</sup>/yr (sinks) in the 1990s and 2000s, respectively (D.P. Turner, Ritts, and others, 2011). A similar trend with an overall smaller magnitude of change was also observed for private forests in the above study. In the forested landscapes of the Northern Rockies, forest thinning, prescribed burning, and mechanical fuel treatment are frequently applied forest-management practices. Such practices have been studied for both the positive and negative effects on restoring the fire regime and reducing fire emissions to the atmosphere; the results were mixed across landscape types in the Western United States. The mechanical fuel treatments were generally found to reduce fire severity, fire risks, and immediate combustion emissions (Stephens and others, 2009; Wiedinmyer and Hurteau, 2010; North and Hurteau, 2011); however, their long-term effects on carbon sequestration in ecosystems were mixed. The use of mechanical fuel treatments and forest thinning as a means to reduce emissions and increase carbon sequestration were found to be ineffective or counterproductive in the Pacific Northwest (Hudiburg and others, 2011; Mitchell and others, 2009) and the Northern Rockies (Reinhardt and Holsinger, 2010), but beneficial in the Sierra Nevada in California (North and Hurteau, 2011).

Grasslands/shrublands are the most prevalent ecosystem types in the Western United States, occupying almost 60 percent of the total land area. They are distributed primarily in the semiarid Great Basin and Colorado Plateau, as well as along the slopes of the major mountain systems. As with the forest ecosystems, carbon storage and sequestration in grasslands/shrublands ecosystems were highly correlated to the moisture gradient and influenced by land-management activities, particularly grazing-intensity management (Lal, 2004; Derner and Schuman, 2007). Heavy grazing during extended seasons may cause changes in species composition (including C<sub>4</sub> grasses replacing C<sub>3</sub> grasses and the dominance of cheatgrass (*Bromus tectorum*) in sagebrush communities), which may lead to a reduced amount of aboveground biomass, accelerated soil decomposition, and a loss of soil organic carbon stock to the atmosphere (Bradley and others, 2006; Derner and Schuman, 2007; Schuman and others, 2009). Reducing (but not necessarily excluding) grazing intensity usually helps improve soil-carbon preservation and sequestration because there is more decomposed vegetation contributing to the soils (Schuman and others, 2009). Although the net flux of carbon per unit of area in arid lands tends to be

small or negligible, grasslands/shrublands cover vast areas; as a result, land use and management still exerts profound effects on the overall carbon balance of the ecosystem (Follett, 2001).

Most of the agricultural lands covered by this assessment are concentrated in the Mediterranean California ecoregion (where mainly orchards and annual vegetable crops are grown) and the Columbia River Basin and Snake River Plain in the Cold Deserts ecoregion (where irrigated row crops, hay, and pastures are dominant). In a study to quantify the effect of agriculture on California's carbon balance, Kroodsma and Field (2006) modeled changes in biomass and soil carbon in all of the agricultural lands in the State. Between 1980 and 2000, the study estimated the average annual net carbon flux for orchards (-26 gC/m<sup>2</sup>/yr), vineyards (-26 gC/m<sup>2</sup>/yr), annual vegetable crops (-14 gC/m<sup>2</sup>/yr), and annual silages (about 0 gC/m<sup>2</sup>/yr), with a mean value of -19 gC/m<sup>2</sup>/yr for all agricultural lands in California. The per-unit-of-area estimate for California was higher than the current-year (2010) EPA estimate (EPA, 2012) for all agricultural lands in the conterminous United States (CONUS), but was much lower than the estimate of -143 gC/m<sup>2</sup>/yr for the State of Oregon (D.P. Turner, Gockede, and others, 2011). In comparison, the assessment conducted for the Great Plains region (Zhu and others, 2011) produced an estimate of -18.8 gC/m<sup>2</sup>/yr for potential carbon sequestration by agricultural lands.

Bridgman and others (2006), who synthesized data from the literature, estimated that wetlands represented 11 percent of the total area of the United States (7 percent in Alaska, 4 percent in the CONUS). Most of the CONUS wetlands are distributed in the Atlantic and Gulf Coast Coastal Plains, the Great Lakes States, and the Great Plains. In the five western ecoregions of this assessment, wetlands represented less than half of one percent of the total area, as mapped using the 1992 NLCD (Vogelmann and others, 2001). Although they noted that uncertainties were very high, Bridgman and others (2006) put the carbon stock and sequestration rates in the wetlands of the CONUS at 19,600 TgC and 17.3 TgC/yr, respectively, which translated to 45.5 kgC/m<sup>2</sup> for the per-unit-of-area of carbon stock and 40.1 gC/m<sup>2</sup>/yr for the per-unit-of-area sequestration rate in the CONUS. The sequestration rate of wetlands in the CONUS was considered to be evenly distributed between peatlands, freshwater mineral soils, and tidal marshes (estuaries). Sequestration in estuaries is mostly accomplished as the result of sedimentation (Bridgman and others, 2006). Brevik and Homburg (2004) found that the net carbon flux in an estuary in southern California averaged -33 gC/m<sup>2</sup>/yr on the basis of an analysis of sediment samples spanning 5,000 years. Chmura and others (2003), however, estimated that sequestration in coastal salt marshes occurs at a much higher rate, ranging from 136.5 gC/m<sup>2</sup>/yr on the East Coast, to 206.3 gC/m<sup>2</sup>/yr in an estuary in southern California, to 296.6 gC/m<sup>2</sup>/yr on the Gulf Coast. Methane



emissions from ecosystems in the CONUS were estimated at approximately 50.4 TgCO<sub>2-eq</sub>/yr (Bridgham and others, 2006) and were mostly emitted from freshwater, mineral-rich soil in wetlands because of its low salinity content (Poffenbarger and others, 2011).

The emission, transport, and sequestration of carbon by aquatic ecosystems should be considered when estimating carbon balances in ecosystems (Chapin and others, 2006; Cole and others, 2007; Tranvik and others, 2009; Aufdenkampe and others, 2011). The existing national-scale studies suggested that lateral transport of carbon fixed within the CONUS and exported to coastal areas can represent between about 10 percent of the total carbon sequestered in forests (trees and soils), croplands, and shrublands (Pacala and others, 2001). Nearly all of the 3.9 to 5.2 gC/m<sup>2</sup>/yr consisted of inorganic carbon. Also, human-made reservoirs can also be sinks for carbon and can sequester between 1.3 and 5.2 gC/m<sup>2</sup>/yr (Pacala and others, 2001). Although the role of

aquatic ecosystems in transporting and sequestering carbon may be well documented for the CONUS, recent global studies have indicated that inland waters can also be sources of carbon emitted into the atmosphere (Cole and others, 2007; Tranvik and others, 2009; Aufdenkampe and others, 2011). The effect of carbon dioxide emissions from lakes and rivers and their roles in regional carbon budgets has yet to be determined for the Western United States.

The above-referenced studies produced a range of net carbon flux estimates that were spatially and temporally variable; however, these estimates also provided a set of reference points against which this assessment may be compared. Table 1.2 provides a summary of the net carbon fluxes per unit of area from a sample of the referenced works for the four major terrestrial ecosystems covered in this assessment. Uncertainties and caveats reported in these studies were not reproduced for the table.

**Table 1.2.** Estimates of the mean net carbon flux per unit of area from a selected sample of studies.

[Three sample estimates are included for each of the four major terrestrial ecosystems: forests, agricultural lands, grasslands/shrublands, and wetlands. CONUS, conterminous United States; EPA, Environmental Protection Agency; gCm<sup>2</sup>/yr, grams of carbon per square meter per year]

Geography	Mean net carbon flux (gC/m <sup>2</sup> /yr)	Source	Timeframe of the sourced work
<b>Forests</b>			
Western States	-90.85	J.E. Smith and Heath (2008)	Early 2000s.
CONUS	-96.75	EPA (2012)	2010.
Oregon	-136	D.P. Turner, Gockede, and others (2011)	Early 2000s.
<b>Agricultural lands</b>			
CONUS	-3.42	EPA (2012)	2010.
Oregon	-143	D.P. Turner, Ritts, and others (2011)	2007.
California	-19	Kroodsma and Field (2006)	1980–2000.
<b>Grasslands/shrublands</b>			
CONUS	-0.97	EPA (2012)	2010.
Oregon <sup>1</sup>	18	D.P. Turner, Ritts, and others (2011)	2007.
Oregon <sup>2</sup>	-7	D.P. Turner, Ritts, and others (2011)	2007.
<b>Wetlands</b>			
CONUS	-40.1	Bridgham and others (2006)	Various, previous decades.
Southern California <sup>3</sup>	-33	Brevik and Homburg (2004)	Over 5,000 years.
Southern California <sup>3</sup>	-206.3	Chmura and others (2003)	1990s.
<b>Aquatic ecosystems</b>			
CONUS <sup>4</sup>	3.9 to 5.2	Pacala and others (2001)	Various, previous decades.
CONUS <sup>5</sup>	-1.3 to 5.2	Pacala and others (2001)	Various, previous decades.

<sup>1</sup>Grasslands only.

<sup>2</sup>Shrublands only.

<sup>3</sup>Specifically, coastal salt marsh.

<sup>4</sup>Inland to coastal carbon export.

<sup>5</sup>Carbon burial in reservoirs.



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