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

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This is the second in a series of reports produced by the U.S. Geological Survey (USGS) to fulfill the requirements of section 712 of the Energy Independence and Security Act (EISA) of 2007 and to conduct a comprehensive national assessment of carbon (C) storage and flux (flow) and the fluxes of other greenhouse gases (GHGs, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)). These carbon and GHG variables were examined in the Western United States for major terrestrial ecosystems (forests, grasslands/shrublands, agricultural lands, and wetlands) and aquatic ecosystems (rivers, streams, lakes, estuaries, and coastal waters) in two time periods: baseline (the first half of the 2000s) and future (projections from baseline to 2050).

The major questions that this assessment attempted to answer included the following: (1) How much carbon was stored in ecosystems of the Western United States? (2) How much carbon could be stored in future years? (3) How were the carbon storage and fluxes in the Western United States influenced by both natural and anthropogenic processes such as land use, wildland fire, and climate change? (4) How might carbon storage, carbon flux, and the natural and anthropogenic processes that influence carbon cycling in western ecosystems vary both geographically and temporally?

The assessment covered 2.66 million square kilometers (km^2) in the Western United States, which is divided into in five level II ecoregions (as defined by the Environmental Protection Agency (EPA)): Western Cordillera, Marine West Coast Forest, Cold Deserts, Warm Deserts, and Mediterranean California. The assessment was based on measured and remotely sensed data collected by the USGS and many other agencies and organizations combined with statistical methods and simulation models. The major findings and discussion follow below.

Baseline and Projected Future Land-Use and Land-Cover Change

- In 2005, the total area of the Western United States (2.66 million km^2) was distributed over these ecosystems: grasslands/shrublands (58.9 percent), forests (28.1 percent), agricultural lands (6.1 percent), water (1.5 percent), wetlands (0.38 percent), and other land types (5.2 percent). Between 1992 and 2005, changes in land use (such as croplands) and land cover (such as wetlands) in the Western United States affected 2.9 percent of that land area and were driven by demands for forest products, urban development, and agriculture. The change in land use and land cover (LULC) from 2006 to 2050 for all ecosystems in the Western United States was projected to be between 5.8 and 7.8 percent. The most active ecoregions of projected land use and cover (LULC) change were the Marine West Coast Forest, Western Cordillera, and Mediterranean California.

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- The projected changes (to 2050) in both LULC and climate were used in this assessment to support the projection of future potential carbon storage and fluxes in relation to both ecological and economic processes. The resulting projections were highly variable across regions as were the assumptions that were made. Between the regions and the assumptions, the overall rates of projected LULC change varied from 1.3 percent to 45 percent. The models of projected climate change (using general circulation model data) indicated (1) a projected general increase in both the mean temperature and in extreme temperatures throughout the Western United States, and (2) a projected high variability in precipitation change that depended on the ecoregion, seasonality, downscaling, and interannual variability.

Baseline Carbon Storage and Flux

- The estimated average total carbon storage in the ecosystems of the Western United States in 2005 was approximately 13,920 (12,418–15,460) teragrams of carbon (TgC), which was distributed in forests (69 percent), grasslands/shrublands (25 percent), agricultural lands (4.3 percent), wetlands (0.46 percent), and other lands (0.63 percent). Geographically, the estimated total and per-unit-of-area carbon stocks ranged from 700.2 TgC (the Cold Deserts) to 8,162.8 TgC (the Western Cordillera) and from 1.5 kilograms of carbon per square meter (kgC/m^2) (the Cold Deserts) to 16.1 kgC/m^2 (the Marine West Coast Forest), respectively. On average, the forests in the Western United States maintained the largest stock of carbon per unit of area among all of the ecosystems at 13.0 kgC/m^2, followed by wetlands (6.3 kgC/m^2), agricultural lands (3.7 kgC/m^2), grasslands/shrublands (2.2 kgC/m^2), and other land types (0.5 kgC/m^2). Overall, live biomass and soil organic carbon (assessed in the top 20-cm-thick layer) accounted for 38 and 39 percent of the total carbon stock, respectively, and woody debris and other surface carbon pools represented the remaining 23 percent.

- The net carbon flux was calculated as the change of carbon stock between two points in time. A negative number indicates carbon uptake, carbon sequestration, or a carbon sink; a positive number indicates a carbon emission or a carbon source. From 2001 to 2005, an average annual net flux of −86.6 (−162.9 to −13.6) TgC/yr was estimated for all of the terrestrial ecosystems in the Western United States. In lakes and reservoirs throughout the Western United States, an additional −2.4 (−3.7 to −1.2) TgC/yr was estimated to be buried and sequestered in sediments. The flux in the Pacific coastal waters was approximately −2.0 TgC/yr. Thus, the combined estimates resulted in a total annual carbon-sequestration rate of −91 TgC/yr across all of the major ecosystems in the Western United States; this rate is equivalent to 4.9 percent of the nation's net fossil-fuel emissions in 2010 as reported by the U.S. Environmental Protection Agency (EPA, 2010). Most of the net carbon flux was in forests (62.2 percent, −72.1 grams of carbon per square meter per year, or $gC/m^2/yr$), followed by grasslands/shrublands (29.6 percent, −16.4 $gC/m^2/yr$), agricultural lands (7.1 percent, −38.3 $gC/m^2/yr$), and wetlands (0.96 percent, −82.1 $gC/m^2/yr$). For comparison, a recent study found that the net carbon fluxes in forests were approximately −93 $gC/m^2/yr$ for the United States as a whole and −103 $gC/m^2/yr$ for the world's temperate forests (Pan, Birdsey, and others, 2011). Of the total carbon sink, live biomass accounted for 32 percent, soil organic matter accounted for 45 percent, and dead biomass accounted for 23 percent.

Projected Future Potential Carbon Storage and Flux

In order to project the future potential carbon storage amounts and flux rates, combinations of LULC scenarios and climate projections, developed on an annual basis between 2006 and 2050, were used along with multiple biogeochemical models for the assessment. The results of these combinations led to a range of estimates for both carbon storage and flux under a range of projected future conditions. The results of projected future potential carbon stock and flux were highly variable among multiple model runs, ecoregions, and ecosystems

- The total amount of carbon that potentially could be stored in the ecosystems of the Western United States in 2050 was projected to range from 13,743 to 19,407 TgC, which is an increase of 1,325 to 3,947 TgC (or 10.7 to 25.5 percent) from baseline conditions of 2005. Among the five ecoregions, the Western Cordillera potentially could store the most carbon, accounting for 60 percent of the projected future total carbon storage for the Western United States, followed by the Cold Deserts (18 percent of the total), Marine West Coast Forest (10 percent), Mediterranean California (8 percent), and Warm Deserts (4 percent). Among the different ecosystems, the forests potentially could store the most carbon, accounting for 70 percent of the total potential carbon storage in the Western United States, followed by grasslands/shrublands (23 percent of the total), and agricultural lands (6 percent).

- The potential mean annual net carbon flux between 2006 and 2050 was projected to range from −113.9 TgC/yr to 2.9 TgC/yr. When compared to the baseline net carbon flux estimates (−162.9 to −13.6 TgC/yr), the projected future carbon-sequestration rates in the Western United States represented a potential decline by 16.5 to 49 TgC/yr. The projected decline came largely from ecosystems of grasslands/shrublands and forests and was distributed mostly in the Western Cordillera ecoregion.

Baseline and Projected Future Potential Wildland Fire Combustion Emissions

Wildland fire is a major ecosystem disturbance in the Western United States that is influenced by changes in both climate and land use and leads to a considerable interannual and regional variability in GHG emissions.

- Between 2001 and 2008 in the Western United States, the burned areas and their GHG emissions from combustion ranged from 3,345 to 25,206 square kilometers per year (km^2/yr), and from 6.8 to 75.3 teragrams of carbon dioxide equivalents per year ($TgCO_{2\text{-eq}}$/yr) (1.9 to 20.6 TgC/yr), respectively, mostly in the Western Cordillera and Cold Deserts ecoregions. The annual average GHG emission from the fires was 36.7 $TgCO_{2\text{-eq}}$/yr (10.0 TgC/yr), which was equivalent to 11.6 percent of the estimated average rate of carbon sequestration by terrestrial ecosystems in the Western United States.

- Under future projections of climate change, the area burned by wildland fires was projected to increase by 31 to 66 percent and the GHG combustion emissions from wildland fires were projected to increase by 28 to 56 percent, relative to baseline conditions. These projections, combined with the projected decline in future terrestrial carbon sequestration, could lead to wildland fire combustion emissions equivalent to 27 to 43 percent of carbon sequestration by terrestrial ecosystems in the Western United States. Under extreme climate conditions, wildland fire emissions were projected to increase 73 to 150 percent relative to baseline conditions. Carbon stored in the arid and semiarid parts of the Western United States is especially vulnerable to wildland-fire emissions.

Carbon Cycling in Aquatic Ecosystems of the Western United States

Carbon cycling in and out of the aquatic ecosystems was studied separately from the terrestrial ecosystems in the Western United States. Carbon fluxes and rates of burial within sediments in inland water bodies and coastal waters were estimated using separate methods. The derived results are as follows.

- Using data collected between the 1970s and the present, rivers and streams throughout the Western United States were estimated to transport between 5.5 and 8.9 (average 7.2) TgC/yr (or an average of 3.4 gC/m^2/yr in yield per unit of area) of dissolved inorganic and total organic carbon annually from upstream sources to estuaries and the coastal oceans, where most was returned to the atmosphere. The emissions of carbon dioxide to the atmosphere from inland waters of the Western United States ranged from 16.8 to 48.7 (average 28.2) TgC/yr (or an average of 14.8 gC/m^2/yr in yield per unit of area); 93 percent of the total emissions were from rivers and streams and 7 percent were from lakes and reservoirs.

- The rate of carbon burial (sequestration) in the sediments in the lakes and reservoirs was estimated to range from −1.2 to −3.7 (average 2.4) TgC/yr (or an average of −1.2 gC/m^2/yr in yield per unit of area), whereas in coastal waters the average burial rate was approximately 2.0 TgC/yr. The estimates of carbon fluxes in aquatic ecosystems were highly variable because of differences in precipitation, topography, lithology, and other controlling processes.

Baseline and Projected Future Greenhouse-Gas Fluxes

- In addition to the baseline net carbon flux estimates (−162.9 to −13.6 TgC/yr, or −597.7 to −50.0 $TgCO_{2\text{-eq}}$/yr), the baseline methane (CH_4) and nitrous oxide (N_2O) flux rates were also estimated and were relatively low and highly variable among ecosystems and ecoregions. Overall, the estimated flux rate of methane during the baseline years ranged from −3.1 to −2.9 $TgCO_{2\text{-eq}}$/yr. The estimated flux rate of nitrous oxide remained stable over the baseline years and averaged 1.7 $TgCO_{2\text{-eq}}$/yr. The balance between the three GHGs was projected to continue to 2050, with a large but weakened sink for CO_2 and a weak sink or source for CH_4 and N_2O, depending on the variability of the projected results.

Limitations of the Assessment Report

The known limitations of the assessment report include the following: (1) Forest thinning and rangeland grazing were not considered in estimating the carbon stocks and fluxes. (2) The effects of conservation and recreation management were not specifically analyzed in this report. (3) Wildland-fire combustion emissions were estimated, but the long-term effects of wildland fires on the production of carbon in ecosystems were not analyzed separately in this report. (4) Methane and nitrous oxide fluxes were projected to future years based on a set of LULC scenarios without considering the effects of climate change projections. (5) The baseline carbon fluxes were estimated for the first time for aquatic ecosystems, but the existing carbon storage in the sediments of the aquatic ecosystems was not estimated. (6) Uncertainties from model runs of different components of the assessment were quantified using simple statistical methods to account for the spread of the estimates. Other sources of uncertainties were described in the report but were not quantified. As a result, the total uncertainty of the assessment is unknown. In addition, there were limitations resulting from the methodology used for the assessment; specifically, (a) the changes in vegetation types or structures as the result of plant succession or climate change were not addressed, and (b) the mapping and modeling of major components (such as LULC and wildland fires) of the assessment were not coupled in a completely integrative modeling system.