Chapter 1. Introduction

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1.1. Requirements

This report is the result of an assessment focused on ecosystems of the State of Alaska and conducted by an interagency and interdisciplinary team composed of scientists from the U.S. Geological Survey (USGS), the U.S. Department of Agriculture (USDA) Forest Service, and the University of Alaska-Fairbanks. The reporting of the assessment results partially fulfills requirements set forth by the U.S. Congress through the Energy Independence and Security Act (EISA) of 2007 for a national carbon sequestration and greenhouse-gas (GHG) flux assessment. The national assessment has been completed for the conterminous United States, with results provided in three separate regional reports (Zhu and others 2011; Zhu and Reed, 2012, 2014). The main outcomes of this Alaska assessment include (1) estimates of the amount of carbon stored in ecosystems (such as forests and wetlands), (2) estimates of the capacity of ecosystems to sequester carbon, (3) estimates of the rate of GHG fluxes in and out of the ecosystems, and (4) evaluation of the effects of processes or driving forces that control ecosystem carbon balance and GHG fluxes. Climate change, ecosystem disturbances, wildfire, land use change, and land management represent the major driving forces, but their relative effects on an ecosystem's potential for carbon sequestration vary regionally within Alaska. Information derived from the assessment is intended to inform mitigation and adaptation policies and land management decisions. This assessment also adds to our scientific understanding of the effects of environmental change on high-latitude ecosystem processes.

The relative importance of driving forces that affect carbon storage and other ecosystem services vary regionally within Alaska (Wolken and others, 2011). For example, ongoing warming in arctic and boreal regions of Alaska, which influences ecosystem disturbances such as wildfire, insect outbreaks, and permafrost degradation, has the potential to substantially alter (1) the exchange of carbon dioxide (CO_2) and methane (CH_4) between ecosystems and the atmosphere and (2) the overall ecosystem carbon balance (Kurz and others, 2008; McGuire and others, 2009, 2010; Hayes and others, 2012; Yuan and others, 2012). The maritime region of southern and southeastern Alaska features dense forest cover and active forest management and other land uses such as recreation and urban centers (Wolken and others, 2011). Forest harvesting and changes in forest management policies have had profound effects on age, composition, carbon stock, and productivity of the temperate moist forests and forested wetlands in southeast Alaska (Leighty and others, 2006). Thus, the dynamics of ecosystem carbon balance and CO_2 and CH_4 exchange of arctic, boreal, and maritime regions of Alaska in response to changes in major driving factors are the focus of this assessment. Arctic tundra, alpine tundra, boreal forests, maritime forests, surface waters (rivers and lakes), and arctic, boreal, and maritime wetlands are the main ecosystem types considered in this assessment.

To support the outcomes of the assessment for the entire State of Alaska, the assessors sought to address questions within regions of Alaska. These questions include (1) what are the magnitudes of carbon pools and fluxes of soil, biomass, and surface waters for different regions of Alaska?; (2) how are changes in fire regime, vegetation distribution, permafrost dynamics, and forest management influencing carbon balance in different regions of Alaska?; and (3) how might estimated sources and sinks of CO_2 and CH_4 of arctic, boreal, and maritime ecosystems change in response to projected changes in climate, fire regime, permafrost dynamics, and forest management?

Unlike the rest of the United States, much of Alaska has not traditionally been included in various resource inventories, nor has the State previously been included in any major national carbon and greenhouse inventory reports. The lack of field data as input into assessment methods, the diverse land cover, and the rapid changes in driving factors were a challenge to the assessors and necessitated the use of methods and models (introduced below) that are different from those used for the conterminous United States.

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1.2. Geography

1.2.1. Reporting Regions for the Inland Waters' Component of the Assessment

The reporting regions for the inland waters' component of this assessment are based on the six main hydrologic units of Alaska: the Arctic Slope (called North Slope in this report), Northwest, Yukon, Southwest, South-Central, and Southeast (Seaber and others, 1987). These regions were chosen as the reporting units because, unlike the Alaska Landscape Conservation Cooperatives used in the terrestrial component of this report as described below, the hydrologic units have boundaries that coincide with natural drainage areas for rivers within the State, as hydrologic data from these units were important for developing estimates on inland water carbon fluxes. Descriptions and a map of the regional hydrologic units are presented in chapter 8.

1.2.2. Reporting Regions for the Terrestrial Component of the Assessment

The five reporting regions for the terrestrial component of this assessment are based on the four large terrestrial Landscape Conservation Cooperatives (LCCs) in Alaska: (1) the Arctic LCC, (2) the Western Alaska LCC, (3) the Northwest Boreal LCC (split into northern and southern reporting regions), and (4) the North Pacific LCC (fig. 1.1). These regions were chosen so that the results of the terrestrial component of the assessment could inform regional consortia of natural resource agencies, which have been organized into these LCCs. The Northwest Boreal LCC was split into two reporting regions because the fire regime is quite different between the northern and southern parts of this LCC, which are separated by the Alaska Range. The boundaries of these LCCs are based on several sources discussed below, including six level II U.S. Environmental Protection Agency (EPA) ecoregions in Alaska (Gallant and others, 1995), which are derived from the ecoregions of Omernik (1987; http://archive.epa.gov/wed/ecoregions/web/html/na_eco.html), listed from north to south: the Alaska Tundra, Brooks Range Tundra, Alaska Boreal Interior, Taiga Cordillera, Boreal Cordillera, and Marine West Coast Forest Ecoregions (fig. 1.2). The following sections provide a brief description of each LCC, list the level III ecoregions, and provide links to additional details for each LCC region. A detailed description of each level III ecoregion, summarizing the climate, physiography, hydrology, and vegetation, can be found in Gallant and others (1995). This geographic characterization provides a foundation for understanding the differences in carbon sequestration and fluxes among LCCs and ecoregions in Alaska.

The LCCs' geographic areas were developed by a team of U.S. Fish and Wildlife Service and U.S. Geological Survey scientists and experts by integrating several data sources

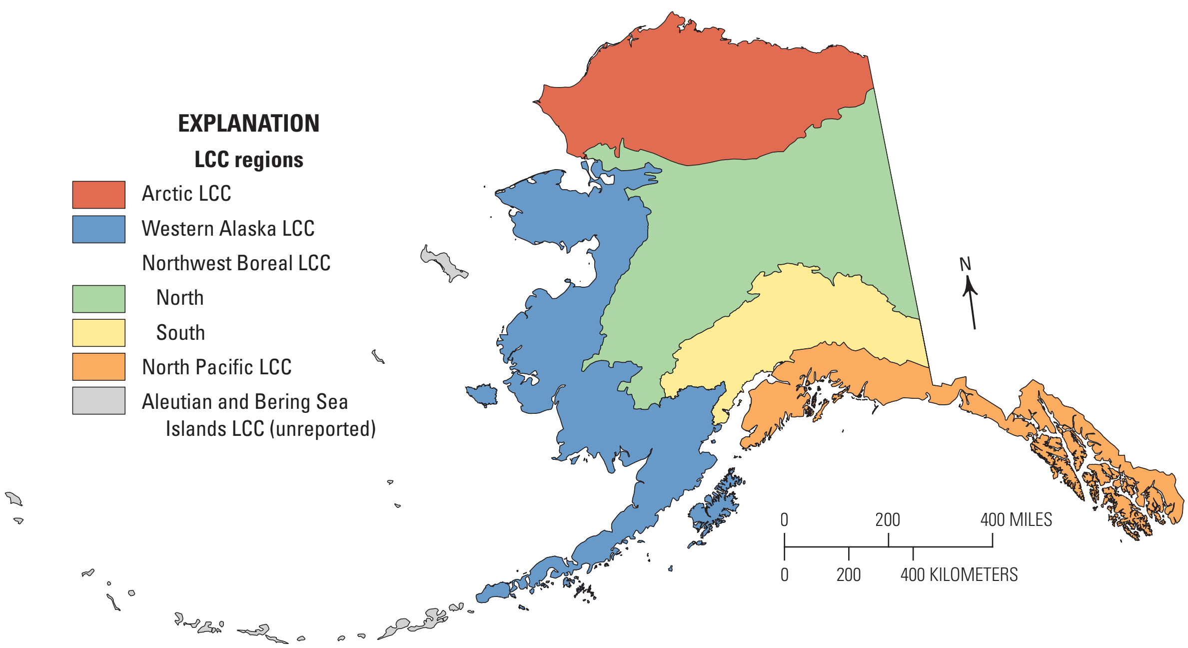

Figure 1.1. Reporting regions considered in this assessment; the regions were based on the boundaries of the Arctic, Western Alaska, Northwest Boreal, and North Pacific Landscape Conservation Cooperatives (LCCs) in Alaska. The land area within the Aleutian and Bering Sea Islands LCC (identified as unreported) was not considered because the models used in this study are poorly suited to represent ecosystem dynamics in this unique region. The Northwest Boreal LCC was divided into northern and southern reporting regions owing to differences in fire regime on either side of the Alaska Range.

(U.S. Fish and Wildlife Service, 2010). First, Bird Conservation Regions (BCRs) were incorporated; they are biologically based units used by long-term partners to facilitate conservation planning and design at landscape scales. To account for aquatic species' needs, the Freshwater Ecoregions of the World, which is the same framework adopted by the National Fish Habitat Action Plan (NFHAP), was incorporated. To account for terrestrial species' needs, Omernik's level II and other existing ecological units were used (U.S. Fish and Wildlife Service, 2010). The resulting geographic framework identified large regions that crossed State and Federal administrative boundaries. In most geographic areas, the boundaries of key partnerships were left intact to preserve existing conservation and science capacities.

1.2.2.1. Arctic Landscape Conservation Cooperative and Associated Ecoregions

The Arctic LCC (www.arcticlcc.org) region includes the Arctic Plains and Mountains Bird Conservation Region (BCR), which spans northern Alaska and Canada. The Arctic LCC encompasses three level III ecoregions: (1) the rugged slopes and valleys of the Brooks Range ecoregion, (2) the rolling hills and plateaus of the Arctic Foothills ecoregion, and (3) the broad, flat Arctic Coastal Plain ecoregion, which is characterized by extensive wetlands and numerous water bodies. The Arctic LCC has arctic climate conditions, with very low mean annual temperatures and very low annual precipitation. It is essentially a treeless region dominated by herbaceous vegetation, although shrub vegetation is found in better drained areas where soil moisture is not limiting. The region is underlain by continuous permafrost. Wildfire is constrained to mesic sites and, although common, represents a minimal amount of the area burned annually statewide.

1.2.2.2. Western Alaska Landscape Conservation Cooperative and Associated Ecoregions

The Western Alaska LCC (https://westernalaskalcc.org/SitePages/Western Alaska LCC.aspx) includes the Western Alaska Bird Conservation Region as well as small portions of the Northwestern Pacific Rainforest and Northwest Interior Forest BCRs. The LCC spans over 1,200 kilometers (km) from north to south and includes a wide diversity of terrain. Landscapes include the permafrost-dominated tundra of the Seward Peninsula, complex delta systems of the Yukon and Kuskokwim Rivers, abundant volcanoes of the Alaska Peninsula, and transitional forests of permafrost-free Kodiak Island. The Western Alaska LCC includes portions of seven level III ecoregions: (1) the Subarctic Coastal Plains, (2) the Seward Peninsula, (3) the Ahklun and Kilbuck Mountains, (4) the Bristol Bay-Nushagak Lowlands, (5) the Alaska Peninsula Mountains, (6) the Interior Forested Lowlands and Uplands, and (7) the Interior Bottomlands ecoregions.

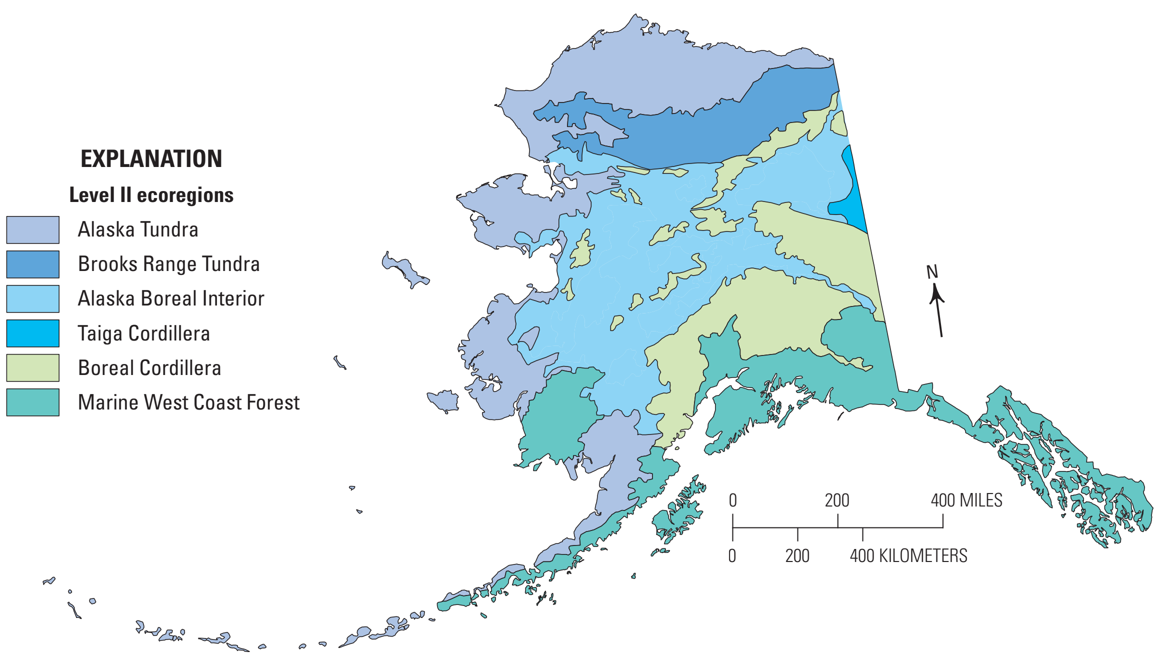

Figure 1.2. The six level II ecoregions for the State of Alaska from Gallant and others (1995).

The climate is transitional between maritime and continental influences, and temperature and precipitation are variable throughout the region. Most of the region is treeless and supports wet to mesic graminoid herbaceous vegetation. Some forest stands are present in valley bottom regions. Permafrost distribution is discontinuous and variable. Wildfires are common in the more mesic portions of the region and range in size from less than 1 to more than 1,000 square kilometers (km^2).

1.2.2.3. Northwest Boreal Landscape Conservation Cooperative and Associated Ecoregions

The Northwest Boreal LCC (http://nwblcc.org/) boundary closely follows that of the Northwestern Interior Forest Bird Conservation Region. The LCC falls within the boreal forest biome and includes south-central and interior Alaska and parts of Canada: most of the Yukon Territory, the northern portion of British Columbia, and a small part of the Northwest Territories. The area includes over 1.3 million km^2 and encompasses large portions of the Yukon, Kuskokwim, Susitna, and Copper River Basins. The Northwest Boreal LCC includes nine level III ecoregions: (1) the Interior Forested Lowlands and Uplands, (2) the Interior Highlands, (3) the Interior Bottomlands, (4) the Yukon Flats, (5) the Ogilvie Mountains, (6) the Cook Inlet, (7) the Alaska Range, (8) the Copper Plateau, and (9) the Wrangell Mountains ecoregions.

The Northwest Boreal LCC domain encompasses not only a very large land area but also significant gradients in climate, hydrology, and disturbance dynamics (particularly with respect to wildfire and insect outbreaks). For this reason, the Northwest Boreal LCC was divided into northern and southern subregions that reflect the substantial differences in climate (continental versus maritime influenced) and disturbance (wildfire versus insects) found on opposite sides of the Alaska Range; the division was based on an existing model's specific subregion calibration related to the "Unified Ecoregions of Alaska" (Nowacki and others, 2003). For assessment reporting purposes throughout the remainder of this report, results are reported for Northwest Boreal LCC North and Northwest Boreal LCC South.

The Northwest Boreal LCC North has a discontinuous permafrost distribution that is highly variable. The region is influenced by a strong continental climate with seasonal temperature extremes and low precipitation. The region is primarily forested. Wildfire is common, and fires range in size from less than 1 to more than 3,000 km^2.

The Northwest Boreal LCC South also has a discontinuous permafrost distribution that is highly variable. The region includes significant high-elevation mountainous terrain. The region is influenced by a maritime climate with variable but relatively high precipitation. The region is primarily forested. Wildfire is common but represents a relatively small proportion of the area burned annually statewide.

1.2.2.4. North Pacific Landscape Conservation Cooperative and Associated Ecoregions in Alaska

The North Pacific LCC (http://northpacificlcc.org/) encompasses the Northwest Pacific Rainforest Bird Conservation Region. The LCC includes the entire range of the Pacific Coastal Temperate Rainforest extending over 3,500 km from Alaska through British Columbia in Canada and into three States in the conterminous United States: Washington, Oregon, and northern California. For this assessment, the focus is on only the portion of the LCC within Alaska. In Alaska, the North Pacific LCC includes three level III ecoregions: (1) the Alaska Peninsula Mountains, (2) the Pacific Coastal Mountains, and (3) the Coastal Western Hemlock-Sitka Spruce Forests ecoregions.

The North Pacific LCC is characterized by complex topography with steep and rugged mountains and significant glaciers and ice fields. Its climate has a maritime influence with moderate temperatures and high but variable annual precipitation ranging from 510 to 3,900 millimeters (mm). Wildfires are rare, usually human caused, and restricted to sizes less than 0.4 km^2. Through 2014, about 452,000 acres of timber have been harvested within the national forest lands of this region (U.S. Department of Agriculture Forest Service, 2014). The region is generally free of permafrost. Forests of western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*) along with western redcedar (*Thuja plicata* Donn ex D. Don) and yellow-cedar (*Callitropsis nootkatensis* (D. Don) D.P. Little; naming after Hennon and others, 2016) are widespread.

1.3. A Brief Overview of Previous Studies of Carbon Dynamics in Alaska

The historical carbon dynamics of ecosystems in Alaska have been studied at local, subregional, and regional scales. Methods of analysis included the use of observations and process-based models. This section summarizes recent syntheses of data on historical carbon storage and dynamics by methodology.

There have been several observational syntheses of data on soil carbon storage in Alaska at the statewide level. These include studies focused on understanding controls over carbon storage across the State, as well as studies focused on estimating the magnitude of carbon storage in the State. Johnson and others (2011) conducted a first-order assessment of the spatial distributions of soil carbon in Alaska from a soil carbon database compiled to better understand controls over soil carbon storage across the State. Temperature and landform type were the dominant controls on soil carbon distribution for selected ecoregions. Mean soil carbon pools (to a depth of 1 meter [m]) varied by threefold, sevenfold, and tenfold across ecoregion, landform, and ecosystem types, respectively. Climate interactions with landform type and soil carbon were greatest in the uplands. For upland soil, there was a sixfold nonlinear increase in soil carbon with a decrease in latitude (that is, with an increasing temperature gradient), where soil carbon was lowest in the intermontane boreal ecoregion compared to the arctic tundra and coastal rainforest regions. Additional factors that appeared to be related to soil carbon distribution within ecoregions included stand age, aspect (direction faced by a slope), and permafrost presence or absence in black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.) stands. Johnson and others (2011) estimated that soil carbon storage to a depth of 1 m in Alaska soils ranged from 14,000 grams of carbon per square meter (gC/m^2) in intermontane boreal forests to 25,000 gC/m^2 in coastal rainforests to 44,000 gC/m^2 in arctic tundra. Bliss and Maursetter (2010) estimated soil organic carbon in Alaska totaling 48 petagrams of carbon (PgC) and used much of the same information as Johnson and others (2011). Using a geostatistical approach, Mishra and Riley (2012) estimated that Alaska soils stored 77 PgC, of which 61 percent was in the active layer, 27 percent was in permafrost, and 12 percent was in nonpermafrost soils. The differences among these estimates indicate that substantial gaps exist in the soil carbon databases used to develop these estimates (see Johnson and others, 2011).

Analyses of vegetation carbon storage in Alaska have focused primarily on forests. Yarie and Billings (2002) estimated that aboveground carbon storage was approximately 400 teragrams of carbon (TgC) (averaging about 2,400 gC/m^2) in the boreal forests of the State; their work was based on several one-time inventories between 1963 and 1994. Leighty and others (2006) and Barrett (2014) estimated that aboveground carbon storage in trees was between 420 and 530 TgC in the Tongass National Forest of southeast Alaska, with another 120 TgC in belowground roots. Barrett and Christensen (2011) estimated that coastal forests of southeast and south-central Alaska stored approximately 650 TgC in aboveground trees. Statewide, these estimates indicate that aboveground carbon of forests in Alaska was likely greater than 1,000 TgC in 2009.

Some observational syntheses of the exchange of carbon with the atmosphere in Alaska have been based largely on scaling of chamber and eddy covariance measurements of CO_2 and CH_4 exchange. Manual chambers, automatic chambers, and eddy covariance towers use infrared gas analyzers that measure CO_2 concentrations. For CH_4, the field technology is less developed and has relied on gas sample collection in the field, with laboratory estimates of CH_4 concentrations made by using gas chromatographs. Eddy covariance measurement systems have recently been developed that allow continuous direct CH_4 concentration estimates in the field, and these are starting to be more commonly used to measure CH_4 exchange.

In an observational synthesis for arctic tundra of North America, which was dominated by measurements made in Alaska, McGuire and others (2012) suggested that arctic tundra in Alaska was an annual source of CO_2 to the atmosphere between 1990 and 2009 of 10±20 gC/m^2 and that the release of CO_2 in winter more than offset the uptake of CO_2 during the summer. Although the synthesis suggested that arctic tundra in Alaska was a source of CO_2 to the atmosphere, the uncertainties include the possibility that it could have been an annual sink of CO_2 between 1990 and 2009. The synthesis also suggested that arctic tundra in Alaska was an annual source of CH_4 to the atmosphere of 5.4±3.5 grams of carbon in methane per square meter ($gC\text{-}CH_4/m^2$) between 1990 and 2009.

In a recent synthesis of eddy covariance studies in Alaska, Ueyama and others (2013) evaluated factors influencing CO_2 exchange in eight Arctic tundra and five boreal ecosystems in the State and found that all of the boreal and seven of the eight Arctic tundra ecosystems acted as CO_2 sinks during the growing season. The analysis revealed that there was a high sensitivity of the sink strength in tundra ecosystems to growing season length, whereas time since fire disturbance played a major role in the sink strength of boreal ecosystems. Thus, the analysis suggested that tundra ecosystems might increase sink strength during the growing season in response to warming, but that an increasing fire frequency would likely decrease sink strength in boreal ecosystems of Alaska.

Some syntheses of the exchange of carbon with the atmosphere within Alaska have been based on the analysis of forest inventory data. The repeated inventory of forests in Alaska has largely been focused on Tongass National Forest in southeast Alaska and Chugach National Forest in south-central Alaska, although some one-time inventories have been conducted in other parts of Alaska. The most recent analyses by the Forest Inventory and Analysis (FIA) program of the USDA Forest Service indicates that forest carbon stocks in southeast and south-central Alaska increased by approximately 6±3 teragrams of carbon per year (TgC/yr) between 1990 and 2013 (U.S. Department of Agriculture Forest Service, 2015). On the basis of the analysis of one-time inventories conducted between 1963 and 1987 outside of maritime coastal Alaska, Yarie and Billings (2002) estimated that boreal forests in Alaska were an annual sink for 9.65 TgC in the last few decades of the last century.

Previous research regarding carbon fluxes of rivers in Alaska has focused on the main stem Yukon River and its tributaries, large rivers that drain the North Slope, and small streams in the southeast. Yukon River total carbon exports have been estimated to be 7.8 TgC/yr, with 70 percent of the total carbon flux as dissolved inorganic carbon (Striegl and others, 2007). For the North Slope, estimates of organic carbon export from the Sagavanirktok, Kuparuk, and Colville Rivers were approximately 0.3 TgC/yr. The Yukon River Basin has an area of 831,000 square kilometers (km^2), and the three North Slope rivers sum to a total drainage area of 80,000 km^2, producing yields of 9.4 grams of carbon per square meter per year ($gC/m^2/yr$) and 2.5 $gC/m^2/yr$, respectively. Rates of stream organic carbon exports for the southeastern regions of Alaska, mainly draining the coastal temperate rain forest, have been estimated as being between 10.5 and 30 $gC/m^2/yr$ (D'Amore and others, 2015).

Riverine CO_2 fluxes to the atmosphere have also been documented in the Yukon River Basin at 7.7 TgC/yr, or 9.2 gC/m^2/yr. These emission rates are roughly equivalent to total lateral carbon transport. Estimates of CO_2 emissions for rivers in the Kuparuk River Basin ranged between 0.02 gC/m^2/yr for the time period of 2001 to 2013 (Cory and others, 2014) and 1.7 gC/m^2/yr for 1994 to 1996 (Hobbie and Kling, 2014). Lake CO_2 fluxes in the North Slope region of Alaska have been documented as being between 0.4 and 1.1 gC/m^2/yr (Cory and others, 2014; Hobbie and Kling, 2014). Many studies of glacial lakes, with objectives that included documenting long-term climate change (Anderson and others, 2001; Yu and others, 2008) and its effects on wildlife population dynamics (Barto, 2004; Rogers and others, 2013), are based on sediment analyses that provide lake carbon burial rates. From these studies and many others, estimates for carbon burial in glacial lakes throughout the State range between 0.62 and 30 gC/m^2/yr (for example, Anderson and others, 2001; Yu and others, 2008; Rogers and others, 2013). Carbon burial estimates for thermokarst lakes in the interior and North Slope regions of Alaska are between 2 and 23 gC/m^2/yr (Lynch and others, 2002; Mann and others, 2002).

Comparisons among Terrestrial Biosphere Models (TBMs) indicate that the models do not agree about whether the North Slope of Alaska is a source or a sink for atmospheric CO_2. An analysis of model output from numerous TBMs indicates that net ecosystem exchange of CO_2 with the atmosphere is -10 ± 190 gC/m^2/yr (the minus sign indicates a sink; Fisher and others, 2014). It is important to note that most of the TBMs in the model comparison represent tundra on the North Slope of Alaska as equivalent to temperate grassland, which is not physiologically representative of the wetland, graminoid, and shrub tundra that occurs on the North Slope. The analysis of TBM output results in inflated estimates of uncertainty about carbon dynamics in Alaska because these TBMs generally do not include processes such as permafrost dynamics and wildfire that are relevant to the region.

An analysis of tundra carbon dynamics in the Arctic Ocean Drainage Basin suggested that arctic tundra has been a weakening sink for atmospheric CO_2 in recent decades because of the effects of climate in enhancing decomposition even though vegetation carbon of tundra was estimated to be increasing (McGuire and others, 2010; Hayes and others, 2011, 2014). An analysis by Euskirchen and others (2009) suggested that vegetation carbon in tundra of the North Slope of Alaska will continue to increase in the 21st century because of longer growing seasons and increased soil nitrogen availability leading to more leaf area, but that soil carbon losses will greatly outpace the gains in vegetation carbon.

An analysis of boreal forest carbon dynamics in the Arctic Ocean Drainage Basin, which is dominated by boreal forest, suggested that boreal forest was transitioning from being a sink to being a source because of the combination of both enhanced decomposition associated with permafrost thaw and an increase in wildfires throughout the region (McGuire and others, 2010; Hayes and others, 2011, 2014). A process-based model analysis of boreal forest carbon dynamics in the Yukon River Basin in Alaska and Canada is consistent with the panboreal analysis, as it indicated that soil carbon stocks would have increased by 158 TgC between 1960 and 2006 if the basin had not undergone warming and changes in fire regime (Yuan and others, 2012). Together, these analyses of the results of process-based models suggest that there is a complex interplay between the effects of climate and wildfire on vegetation and soil carbon dynamics, and that both climate and wildfire can influence these dynamics through effects on permafrost.

Similar to the analysis of CO_2 exchange, comparisons among TBMs indicate that the models do not agree about whether the North Slope of Alaska is a source or a sink for atmospheric CH_4. An analysis of model output from several CH_4 models indicated that emissions were estimated to be 2.52 ± 4.02 grams of methane per square meter per year (gCH_4/m^2/yr) in the early 2000s (Fisher and others, 2014). Another analysis indicated that estimated emissions of CH_4 between 1980 and 1996 were 4.01 gCH_4/m^2/yr in tundra of the North Slope of Alaska, 2.00 gCH_4/m^2/yr in interior Alaska, and 0.99 gCH_4/m^2/yr in southern Alaska (Zhuang and others, 2007). Zhuang and others (2007) estimated that combined emissions for Alaska between 1980 and 1996 were approximately 3 teragrams of methane per year (TgCH_4/yr), which is somewhat higher than the estimate of 2.1 teragrams of methane (TgCH_4) for Alaska from May to September 2012 that was based on data from an aircraft sampling campaign (Chang and others, 2014). The analysis by Zhuang and others (2007) further estimated that climate change would cause CH_4 emissions to increase by 58 percent in northern Alaska, 77 percent in interior Alaska, and 153 percent in southern Alaska by the end of the 21st century. Sensitivity analysis in the study indicated that soil temperature and depth to water table were the two most important drivers influencing changes in emissions. This regional analysis suggests that the response of methane emissions depends on interactions between changes in projected temperature and soil hydrology.

In summary, analyses to date have indicated substantial variability in estimates of carbon pools and carbon fluxes in Alaska. Estimates of soil carbon storage varied from 48 to 77 PgC. Estimates of total vegetation carbon at the statewide scale have not been formally assessed; however, estimates of vegetation carbon storage conducted for forests at the regional scale indicated that aboveground carbon is likely greater than 1,000 TgC at the statewide scale. Analyses of carbon fluxes in tundra and boreal forests in Alaska indicate substantial uncertainty as these ecosystems have been estimated to be both sources and sinks for atmospheric CO_2 in different studies. There is general agreement that maritime forests of Alaska are a sink for atmospheric CO_2 of less than 10 TgC/yr. Although analyses indicate that there are substantive fluxes of carbon from inland waters in some hydrologic basins of Alaska, these fluxes have not yet been estimated for all inland waters in Alaska. Finally, analyses of CH_4 emissions for Alaska are quite variable and indicate substantial uncertainty.

1.4. Overall Methodology

The methodology developed for this assessment was designed to produce a scientific synthesis of carbon dynamics in the State that would be useful both to stakeholders in Alaska and to State, national, and international decision makers. This goal required the organization of input data for the State and technical components to make use of these data (fig. 1.3). The technical components include (1) the organization of input data for models and data syntheses; (2) modeling of processes in biogeography, fire regime, permafrost, and hydrologic dynamics; (3) syntheses of carbon dynamics via biogeochemical modeling for upland and wetland ecosystems, empirical syntheses of carbon cycling for ecosystems in south-central and southeast coastal Alaska, and syntheses of carbon fluxes for surface waters of Alaska; and (4) analysis, synthesis, report development, data distribution, and communication of results to stakeholders. The assessment is prepared for a historical period (1950–2009) and a future projection period (2010–2099).

Input data were organized for soil carbon; soil texture; permafrost distribution; active-layer thickness; vegetation carbon; historical forest harvest; future forest management; land-cover distribution; fire disturbance; wetland and surface-water distribution; historical and future climate; upland and wetland biogeochemistry; and the transport, emission, and burial of aquatic carbon. The historical and future climate and fire disturbance datasets are described in chapter 2; data syntheses for soil carbon, permafrost, and soil texture are described in chapter 3; biogeochemical cycling, vegetation biomass, historical forest harvest, and future forest management scenarios for forests in south-central and southeast Alaska are described in chapters 4 and 5; upland extent and biogeochemistry are described in chapter 6; wetland extent and biogeochemistry are described in chapter 7; and the transport, emission, and burial of aquatic carbon are described in chapter 8.

The assessment uses the Alaska Frame-Based Ecosystem Code (ALFRESCO; Rupp and others, 2000, 2002) to simulate changes in fire regime and vegetation distribution from 2010 through 2099. ALFRESCO was calibrated on the basis of historical data about fire occurrence for Alaska from 1950 through 2009 (see chapter 2 for more details). The contemporary spatial distribution of permafrost was estimated by two different empirical approaches (see chapter 3). The empirical estimates were then used to validate permafrost simulation for the historical period (1950–2009) by the Dynamic Organic Soil version of the Terrestrial Ecosystem Model (DOS-TEM; Yi, Manies, and others, 2009; Yi, McGuire, and others, 2009; Yi and others, 2010; Yuan and others, 2012; Genet and others, 2013).

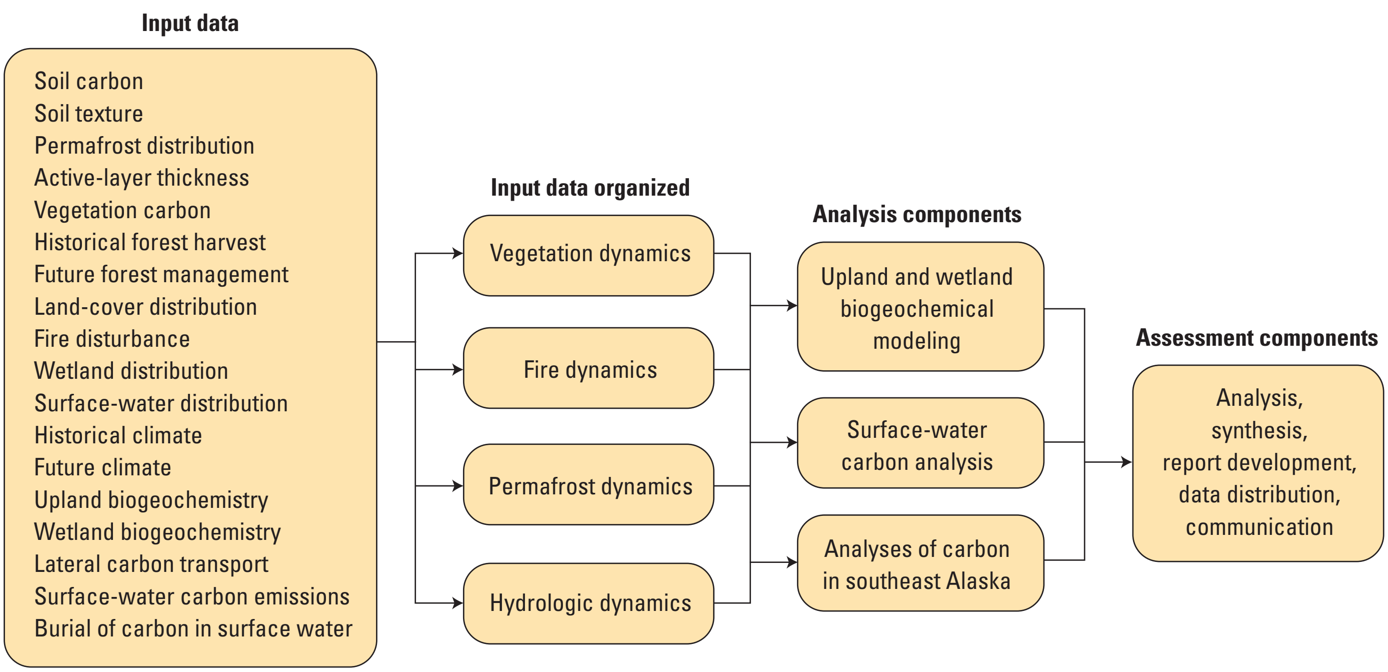

Figure 1.3. The general methodology used in the assessment of carbon storage and fluxes in Alaska. Input data were organized to provide information used to assess historical and future changes in vegetation, fire, permafrost, and hydrologic dynamics. The data on these changes were then used to assess carbon dynamics of inland aquatic ecosystems for the historical period (1950–2009) and carbon dynamics of upland and wetland ecosystems for the historical period and the future projection period (2010–2099). The results of these carbon assessments have been synthesized and are summarized in this report. The data from this assessment are being made available for distribution.

The DOS-TEM model used input data on soil texture, land cover, historical climate, historical fire, historical forest harvest, and model projections of future climate, fire disturbance, and forest management to estimate changes in ecosystem pools and fluxes for the two time periods for upland and wetland ecosystems. In addition, these upland and wetland estimates were also separately evaluated as described in chapters 6 and 7. The Methane Dynamics Module of the Terrestrial Ecosystem Model (MDM-TEM; Zhuang and others, 2004, 2007) was used to estimate methane consumption in upland ecosystems (chapter 6) and both methane consumption and emissions in wetland ecosystems (chapter 7). An empirical model was used to estimate contemporary net ecosystem carbon balance of forest ecosystems in southeast Alaska (chapter 4). A Forest Vegetation Simulator (FVS) model was also used, together with FIA forest inventory data, for estimating contemporary and future forest carbon balance in relation to management actions in south-central and southeast coastal Alaska (chapter 5).

A statewide map of lake area (U.S. Geological Survey, 2012); modeled discharge, velocity and width values for streams (Kost and others, 2002); carbon concentration in surface waters; and carbon burial rates in lakes were assimilated into empirical models to estimate regional and statewide estimates of carbon transport, emission, and burial in aquatic ecosystems of Alaska (chapter 8).

1.5. Land-Cover Maps Used in the Assessment

To make comparisons between various aspects of this assessment, a common land-cover classification was required; this section describes the development of the common land-cover classification used for the assessment from existing land-cover maps. Other datasets used in the assessment are described in various chapters, as indicated above. The definition of land-cover types in the common land-cover classification we developed for this assessment was primarily driven by the needs of ALFRESCO and DOS-TEM, which required highly aggregated land-cover types. Remote-sensing datasets defining land cover for Alaska and western Canada were used to develop more aggregated baseline vegetation input data as the spatial foundation for the assessment. These input datasets represented highly modified output originating from the North American Land Change Monitoring System 2005 (NALCMS 2005) dataset (North American Land Change Monitoring System, 2010; for arctic and subarctic ecosystem types) and the National Land Cover Database (NLCD) 2001 (Homer and others, 2007; for coastal maritime ecosystem types). The NALCMS 2005 data were originally at a 250-m resolution and the NLCD at a 30-m resolution. The modified input data from both datasets were resampled to a consistent 1-km resolution to reduce the volume of data and meet modeling requirements.

Several adjustments were made to the thematic classes to facilitate this assessment and to correspond with the capabilities of the methods used. To define land-cover types for the Arctic, Western Alaska, and Northwest Boreal LCCs, the NALCMS 2005 classes were adjusted to represent the general land-cover types of black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.) forest, white spruce (*Picea glauca* (Moench) Voss) forest, deciduous forest, shrub tundra, graminoid tundra, wetland tundra (including wet-sedge and tussock tundra), and heath tundra. Partitioning of coniferous forest into late successional spruce forest types was based on topographic position. Tundra land-cover types were partitioned primarily on the basis of ecoregion distribution and growing season temperature thresholds; the Circumpolar Arctic Vegetation Map (CAVM Team, 2003) was used to define the tree line. Heath tundra includes xeric ecosystems dominated by lichen crust and moss and was defined as high-elevation barren land not covered by snow or ice, as well as land included in the barren lichen-moss classes from the NALCMS 2005 classification. For this assessment, the NALCMS 2005 classes did not adequately represent the land-cover types of the maritime zone in the North Pacific LCC region of Alaska and in the vicinity of Kodiak Island. Therefore, NLCD 2001 classes were adjusted to represent land-cover types specific to the maritime zone: maritime upland forest, maritime wetland forest, maritime alder shrubland, and maritime fen. The correlation between the general NLCD classification and the maritime land-cover types was determined through spatial comparison with local vegetation maps.

1.6. Organization of the Report

This report has an executive summary followed by nine chapters, which are briefly described below. Each chapter has its own references cited list.

Chapter 1 (Introduction) describes the requirements of this assessment, the geography of Alaska, the previous understanding of carbon dynamics in Alaska, the overall methodology of the assessment, the strategy for the land-cover maps used in the assessment, and the organization of the report.

Chapter 2 (Climate Simulations, Land Cover, and Wildfire in Alaska) describes historical observations of climate and wildfire, the downscaling and development of climate data, and results from the application of ALFRESCO to simulate changes in vegetation distribution and wildfire from 2010 through 2099.

Chapter 3 (Soil Carbon and Permafrost Estimates and Susceptibility to Climate Change in Alaska) reports on syntheses of data about soil carbon, permafrost (distribution and active-layer thickness), and soil texture for Alaska. A key feature of this chapter is the comparison of DOS-TEM outputs with these data syntheses.

Chapter 4 (Watershed Carbon Budgets in the Southeastern Alaskan Coastal Forest Region) reports results from an empirical model based on a synthesis of carbon cycling data from southeast Alaska.

Chapter 5 (Forest Inventory-Based Analysis and Projections of Forest Carbon Stocks and Changes in Alaska Coastal Forests) reports results of outputs from the USDA Forest Service Forest Vegetation Simulator (FVS) for contemporary conditions and for future forest management scenarios.

Chapter 6 (Terrestrial Carbon Modeling: Baseline and Projections in Upland Ecosystems of Alaska) reports on simulated changes in carbon pools and fluxes for the historical (1950–2009) and future projection (2010–2099) periods for upland terrestrial ecosystems of Alaska.

Chapter 7 (Terrestrial Carbon Modeling: Baseline and Projections in Lowland Ecosystems of Alaska) reports on the simulated changes in carbon pools and fluxes for the historical (1950–2009) and future projection (2010–2099) periods for wetland terrestrial ecosystems of Alaska.

Chapter 8 (Carbon Transport, Emission, and Burial from Inland Aquatic Ecosystems in Alaska) reports on contemporary estimates of the transport of carbon to coastal ecosystems, emissions of carbon from inland aquatic ecosystems to the atmosphere, and carbon burial in inland aquatic ecosystems based on syntheses of data for Alaska.

Chapter 9 (Alaska Carbon Balance) reports on the integrated carbon balance of the entire State of Alaska for the historical (1950–2009) and future projection (2010–2099) periods based on a synthesis of estimates from the other chapters in this report. The carbon balance estimates at the regional scale can be found in chapters 6, 7, and 8. This chapter is intended as a summary for use by those interested in the role that the State of Alaska plays in national and international carbon budgets.

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1.8. References Cited

Anderson, Lesleigh, Abbott, M.B., and Finney, B.P., 2001, Holocene climate inferred from oxygen isotope ratios in lake sediments, central Brooks Range, Alaska: Quaternary Research, v. 55, no. 3, p. 313–321, http://dx.doi.org/10.1006/qres.2001.2219.

Barrett, T.M., 2014, Storage and flux of carbon in live trees, snags, and logs in the Chugach and Tongass National Forests: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report PNW–GTR–889, 44 p. [Also available at http://www.fs.fed.us/pnw/pubs/pnw_gtr889.pdf.]

Barrett, T.M., and Christensen, G.A., tech. eds., 2011, Forests of southeast and south-central Alaska, 2004–2008; Five-year forest inventory and analysis report: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report PNW–GTR–835, 156 p. [Also available at http://www.fs.fed.us/pnw/pubs/pnw_gtr835.pdf.]

Barto, David, 2004, Assessing the production of sockeye salmon (*Oncorhynchus nerka*) at Chilkat Lake, southeast Alaska, using current trophic conditions and the paleolimnologic sediment record: Fairbanks, Alaska, University of Alaska, M.S. thesis, 111 p.

Bliss, N.B., and Maursetter, John, 2010, Soil organic carbon stocks in Alaska estimated with spatial and pedon data: Soil Science Society of America Journal, v. 74, no. 2, p. 565–579, http://dx.doi.org/10.2136/sssaj2008.0404.

CAVM [Circumpolar Arctic Vegetation Map] Team, 2003, Circumpolar Arctic vegetation map: U.S. Fish and Wildlife Service Conservation of Arctic Flora and Fauna (CAFF) Map No. 1, scale 1:7,500,000, http://www.geobotany.uaf.edu/cavm/.

Chang, R.Y.-W., Miller, C.E., Dinardo, S.J., Karion, Anna, Sweeney, Colm, Daube, B.C., Henderson, J.M., Mountain, M.E., Eluszkiewicz, Janusz, Miller, J.B., Bruhwiler, L.M.P., and Wofsy, S.C., 2014, Methane emissions from Alaska in 2012 from CARVE airborne observations: National Academy of Science Proceedings, v. 111, no. 47, p. 16694–16699, http://dx.doi.org/10.1073/pnas.1412953111.

Cory, R.M., Ward, C.P., Crump, B.C., and Kling, G.W., 2014, Sunlight controls water column processing of carbon in arctic fresh waters: Science, v. 345, no. 6199, p. 925–928, http://dx.doi.org/10.1126/science.1253119.

D'Amore, D.V., Edwards, R.T., Herendeen, P.A., Hood, Eran, and Fellman, J.B., 2015, Dissolved organic carbon fluxes from hydropedologic units in Alaskan coastal temperate rainforest watersheds: Soil Science Society of America Journal, v. 79, no. 2, p. 378–388, http://dx.doi.org/10.2136/sssaj2014.09.0380.

Euskirchen, E.S., McGuire, A.D., Chapin, F.S., III, Yi, S., and Thompson, C.C., 2009, Changes in vegetation in northern Alaska under scenarios of climate change 2003–2100; Implications for climate feedbacks: Ecological Applications, v. 19, no. 4, p. 1022–1043, http://dx.doi.org/10.1890/08-0806.1.

Fisher, J.B., Sikka, M., Oechel, W.C., Huntzinger, D.N., Melton, J.R., Koven, C.D., Ahlström, A., Arain, M.A., Baker, I., Chen, J.M., Ciais, P., Davidson, C., Dietze, M., El-Masri, B., Hayes, D., Huntingford, C., Jain, A.K., Levy, P.E., Lomas, M.R., Poulter, B., Price, D., Sahoo, A.K., Schaefer, K., Tian, H., Tomelleri, E., Verbeeck, H., Viovy, N., Wania, R., Zeng, N., and Miller, C.E., 2014, Carbon cycle uncertainty in the Alaskan Arctic: Biogeosciences, v. 11, p. 4271–4288, http://dx.doi.org/10.5194/bg-11-4271-2014.

Gallant, A.L., Binnian, E.F. Omernik, J.M., and Shasby, M.B., 1995, Ecoregions of Alaska: U.S. Geological Survey Professional Paper 1567, 73 p., 1 pl., scale 1:5,000,00. [Also available at http://pubs.er.usgs.gov/publication/pp1567.]

Genet, H., McGuire, A.D., Barrett, K., Breen, A., Euskirchen, E.S., Johnstone, J.F., Kasischke, E.S., Melvin, A.M., Bennett, A., Mack, M.C., Rupp, T.S., Schuur, E.A.G., Turetsky, M.R., and Yuan, F., 2013, Modeling the effects of fire severity and climate warming on active layer thickness and soil carbon storage of black spruce forests across the landscape in interior Alaska: Environmental Research Letters, v. 8, no. 4, letter 045016, 13 p., http://dx.doi.org/10.1088/1748-9326/8/4/045016.

Hayes, D.J., Kicklighter, D.W., McGuire, A.D., Chen, Min, Zhuang, Qianlai, Yuan, Fengming, Melillo, J.M., and Wullschleger, S.D., 2014, The impacts of recent permafrost thaw on land-atmosphere greenhouse gas exchange: Environmental Research Letters, v. 9, no. 4, letter 045005, 12 p., http://dx.doi.org/10.1088/1748-9326/9/4/045005.

Hayes, D.J., McGuire, A.D., Kicklighter, D.W., Gurney, K.R., Burnside, T.J., and Melillo, J.M., 2011, Is the northern high latitude land-based CO_2 sink weakening?: Global Biogeochemical Cycles, v. 25, no. 3, article GB3018, 14 p., http://dx.doi.org/10.1029/2010GB003813.

Hayes, D.J., Turner, D.P., Stinson, Graham, McGuire, A.D., Wei, Yaxing, West, T.O., Heath, L.S., de Jong, Bernardus, McConkey, B.G., Birdsey, R.A., Kurz, W.A., Jacobson, A.R., Huntzinger, D.N., Pan, Yude, Post, W.M., and Cook, R.B., 2012, Reconciling estimates of the contemporary North American carbon balance among terrestrial biosphere models, atmospheric inversions and a new approach for estimating net ecosystem exchange from inventory-based data: Global Change Biology, v. 18, no. 4, p. 1282–1299, http://dx.doi.org/10.1111/j.1365-2486.2011.02627.x.

Hennon, P.E., McKenzie, C.M., D'Amore, D.V., Wittwer, D.T., Mulvey, R.L., Lamb, M.S., Biles, F.E., and Cronn, R.C., 2016, General information on yellow-cedar, *in* A climate adaptation strategy for conservation and management of yellow-cedar in Alaska: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report PNW–GTR–917, p. 11–13. [Also available at http://www.fs.fed.us/pnw/pubs/pnw_gtr917.pdf.]

Hobbie, J.E., and Kling, G.W., eds., 2014, Alaska's changing Arctic; Ecological consequences for tundra, streams, and lakes: New York, Oxford University Press, 321 p.

Homer, Collin, Dewitz, Jon, Fry, Joyce, Coan, Michael, Hossain, Nazmul, Larson, Charles, Herold, Nate, McKerrow, Alexa, VanDriel, J.N., and Wickham, James, 2007, Completion of the 2001 National Land Cover Database for the conterminous United States: Photogrammetric Engineering and Remote Sensing, v. 73, no. 4, p. 337–341. [Also available at http://www.asprs.org/a/publications/pers/2007journal/april/highlight.pdf.]

Johnson, K.D., Harden, Jennifer, McGuire, A.D., Bliss, N.B., Bockheim, J.G., Clark, Mark, Nettleton-Hollingsworth, Teresa, Jorgenson, M.T, Kane, E.S., Mack, Michelle, O'Donnell, Jonathan, Ping, C.-L., Schuur, E.A.G., Turetsky, M.R., and Valentine, D.W., 2011, Soil carbon distribution in Alaska in relation to soil-forming factors: Geoderma, v. 167–168, p. 71–84, http://dx.doi.org/10.1016/j.geoderma.2011.10.006.

Kost, J.R., Verdin, K.L., Worstell, B.B., and Kelly, G.G., 2002, Methods and tools for the development of hydrologically conditioned elevation data and derivatives for national applications, *in* 2nd Annual Conference on Watershed Modeling, Las Vegas, Nev., 2002: 12 p., accessed February 24, 2015, at http://edna.usgs.gov/Edna/pubs/KostEDNA.pdf.

Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T., and Safranyik, L., 2008, Mountain pine beetle and forest carbon feedback to climate change: Nature, v. 452, no. 7190, p. 987–990, http://dx.doi.org/10.1038/nature06777.

Leighty, W.W., Hamburg, S.P., and Caouette, John, 2006, Effects of management on carbon sequestration in forest biomass in southeast Alaska: Ecosystems, v. 9, no. 7, p. 1051–1065, http://dx.doi.org/10.1007/s10021-005-0028-3.

Lynch, J.A., Clark, J.S., Bigelow, N.H., Edwards, M.E., and Finney, B.P., 2002, Geographic and temporal variations in fire history in boreal ecosystems of Alaska: Journal of Geophysical Research; Atmospheres, v. 107, no. D1, p. FFR 8–1 to FFR 8–17, http://dx.doi.org/10.1029/2001JD000332.

Mann, D.H., Heiser, P.A., and Finney, B.P., 2002, Holocene history of the Great Kobuk Sand Dunes, northwestern Alaska: Quaternary Science Reviews, v. 21, nos. 4–6, p. 709–731, http://dx.doi.org/10.1016/S0277-3791(01)00120-2.

McGuire, A.D., Anderson, L.G., Christensen, T.R., Dallimore, Scott, Guo, Laodong, Hayes, D.J., Heimann, Martin, Lorenson, T.D., Macdonald, R.W., and Roulet, Nigel, 2009, Sensitivity of the carbon cycle in the Arctic to climate change: Ecological Monographs, v. 79, no. 4, p. 523–555, http://dx.doi.org/10.1890/08-2025.1.

McGuire, A.D., Christensen, T.R., Hayes, D., Heroult, A., Euskirchen, E., Kimball, J.S., Koven, C., Lefleur, P., Miller, P.A., Peylin, P., Oechel, W., Williams, M., and Yi, Y., 2012, An assessment of the carbon balance of Arctic tundra; Comparisons among observations, process models, and atmospheric inversions: Biogeosciences, v. 9, p. 3185–3204, http://dx.doi.org/10.5194/bg-9-3185-2012.

McGuire, A.D., Hayes, D.J., Kicklighter, D.W., Manizza, M., Zhuang, Q., Chen, M., Follows, M.J., Gurney, K.R., McClelland, J.W., Melillo, J.M., Peterson, B.J., and Prinn, R.G., 2010, An analysis of the carbon balance of the Arctic Basin from 1997 to 2006: Tellus; Series B, Chemical and Physical Meteorology, v. 62B, no. 5, p. 455–474, http://dx.doi.org/10.1111/j.1600-0889.2010.00497.x.

Mishra, U., and Riley, W.J., 2012, Alaskan soil carbon stocks; spatial variability and dependence on environmental factors: Biogeosciences, v. 9, no. 9, p. 3637–3645, http://dx.doi.org/10.5194/bg-9-3637-2012.

North American Land Change Monitoring System, 2010, 2005 North American land cover at 250 m spatial resolution (edition 1.0): Natural Resources Canada/Canadian Center for Remote Sensing (NRCan/CCRS), United States Geological Survey (USGS); Insituto Nacional de Estadística y Geografía (INEGI), Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), and Comisión Nacional Forestal (CONAFOR), accessed October 30, 2011, at http://www.cec.org/tools-and-resources/map-files/land-cover-2005.

Nowacki, Gregory, Spencer, Page, Fleming, Michael, Brock, Terry, and Jorgenson, Torre, 2003, Unified ecoregions of Alaska; 2001: U.S. Geological Survey Open-File Report 02–297, 1 map. [Also available at http://agdc.usgs.gov/data/usgs/erosafo/ecoreg/index.html.]

Omernik, J.M., 1987, Ecoregions of the conterminous United States: Annals of the Association of American Geographers, v. 77, no. 1, p. 118–125, map supplement, scale 1:7,500,000, http://dx.doi.org/10.1111/j.1467-8306.1987.tb00149.x.

Rogers, L.A., Schindler, D.E., Lisi, P.J., Holtgrieve, G.W., Leavitt, P.R., Bunting, Lynda, Finney, B.P., Selbie, D.T., Chen, Guangjie, and Gregory-Eaves, Irene, 2013, Centennial-scale fluctuations and regional complexity characterize Pacific salmon population dynamics over the past five centuries: National Academy of Sciences Proceedings, v. 110, no. 5, p. 1750–1755, http://dx.doi.org/10.1073/pnas.1212858110.

Rupp, T.S., Starfield, A.M., and Chapin, F.S., III, 2000, A frame-based spatially explicit model of subarctic vegetation response to climatic change; Comparison with a point model: Landscape Ecology, v. 15, no. 4, p. 383–400, http://dx.doi.org/10.1023/A:1008168418778.

Rupp, T.S., Starfield, A.M., Chapin, F.S., III, and Duffy, P., 2002, Modeling the impact of black spruce on the fire regime of Alaskan boreal forest: Climatic Change, v. 55, nos. 1–2, p. 213–233, http://dx.doi.org/10.1023/A:1020247405652.

Seaber, P.R., Kapinos, F.P., and Knapp, G.L., 1987, Hydrologic units maps: U.S. Geological Survey Water-Supply Paper 2294, 63 p., 1 pl., scale 1:7,500,000. [Also available at http://pubs.usgs.gov/wsp/wsp2294/.]

Striegl, R.G., Dornblaser, M.M., Aiken, G.R., Wickland, K.P., and Raymond, P.A., 2007, Carbon export and cycling by the Yukon, Tanana, and Porcupine Rivers, Alaska, 2001–2005: Water Resources Research, v. 43, no. 2, article W02411, http://dx.doi.org/10.1029/2006WR005201.

Ueyama, Masahito, Iwata, Hiroki, Harazono, Yoshinobu, Euskirchen, E.S., Oechel, W.C., and Zona, Donatella, 2013, Growing season and spatial variations of carbon fluxes of Arctic and boreal ecosystems in Alaska (USA): Ecological Applications, v. 23, no. 8, p. 1798–1816, http://dx.doi.org/10.1890/11-0875.1.

U.S. Department of Agriculture Forest Service, 2014, Tongass young growth management strategy 2014: U.S. Department of Agriculture Forest Service, Tongass National Forest, 39 p.

U.S. Department of Agriculture Forest Service, 2015, Baseline estimates of carbon stocks in forests and harvested wood products for National Forest System Units; Alaska region: U.S. Department of Agriculture Forest Service, whitepaper, 34 p., http://www.fs.fed.us/climatechange/documents/AlaskaRegionCarbonAssessment.pdf.

U.S. Fish and Wildlife Service, 2010, Developing the National Geographic Framework: U.S. Fish and Wildlife Service, LCC Information Bulletin, no. 2, 18 p., http://lccnetwork.org/sites/default/files/Resources/LCC_Bulletin_2.pdf.

U.S. Geological Survey, 2012, National Hydrography Dataset: U.S. Geological Survey dataset, accessed March 19, 2015, at http://nhd.usgs.gov.

Wolken, J.M., Hollingsworth, T.N., Rupp, T.S., Chapin, F.S., III, Trainor, S.F., Barrett, T.M., Sullivan, P.F., McGuire, A.D., Euskirchen, E.S., Hennon, P.E., Beever, E.A., Conn, J.S., Crone, L.K., D’Amore, D.V., Fresco, Nancy, Hanley, T.A., Kielland, Knut, Kruse, J.J., Patterson, Trista, Schuur, E.A.G., Verbyla, D.L., and Yarie, John, 2011, Evidence and implications of recent and projected climate change in Alaska’s forest ecosystems: Ecosphere, v. 2, no. 11, article 124, 35 p., http://dx.doi.org/10.1890/ES11-00288.1.

Yarie, John, and Billings, Sharon, 2002, Carbon balance of the taiga forest within Alaska; Present and future: Canadian Journal of Forest Research, v. 32, no. 5, p. 757–767, http://dx.doi.org/10.1139/x01-075.

Yi, Shuhua, Manies, Kristen, Harden, Jennifer, and McGuire, A.D., 2009, Characteristics of organic soil in black spruce forests; Implications for the application of land surface and ecosystem models in cold regions: Geophysical Research Letters, v. 36, no. 5, letter L05501, 5 p., http://dx.doi.org/10.1029/2008GL037014.

Yi, Shuhua, McGuire, A.D., Harden, Jennifer, Kasischke, Eric, Manies, Kristen, Hinzman, Larry, Liljedahl, Anna, Randerson, Jim, Liu, Heping, Romanovsky, Vladimir, Marchenko, Sergei, and Kim, Yongwon, 2009, Interactions between soil thermal and hydrological dynamics in the response of Alaska ecosystems to fire disturbance: Journal of Geophysical Research; Biogeosciences, v. 114, no. G2, article G02015, 20 p., http://dx.doi.org/10.1029/2008JG000841.

Yi, Shuhua, McGuire, A.D., Kasischke, Eric, Harden, Jennifer, Manies, Kristen, Mack, Michelle, and Turetsky, Merritt, 2010, A dynamic organic soil biogeochemical model for simulating the effects of wildfire on soil environmental conditions and carbon dynamics of black spruce forests: Journal of Geophysical Research; Biogeosciences, v. 115, no. G4, article G04015, 15 p., http://dx.doi.org/10.1029/2010JG001302.

Yu, Zicheng, Walker, K.N., Evenson, E.B., and Hajdas, Irka, 2008, Lateglacial and early Holocene climate oscillations in the Matanuska Valley, south-central Alaska: Quaternary Science Reviews, v. 27, nos. 1–2, p. 148–161, http://dx.doi.org/10.1016/j.quascirev.2007.02.020.

Yuan, F.-M, Yi, S.-H., McGuire, A.D., Johnson, K.D., Liang, J., Harden, J.W., Kasischke, E.S., and Kurz, W.A., 2012, Assessment of historical boreal forest C dynamics in the Yukon River Basin; Relative roles of warming and fire regime change: Ecological Applications, v. 22, no. 8, p. 2091–2109, http://dx.doi.org/10.1890/11-1957.1.

Zhu, Zhiliang, ed., Bouchard, Michelle, Butman, David, Hawbaker, Todd, Li, Zhengpeng, Liu, Jinxun, Liu, Shuguang, McDonald, Cory, Reker, Ryan, Sayler, Kristi, Sleeter, Benjamin, Sohl, Terry, Stackpoole, Sarah, Wein, Anne, and Zhu, Zhiliang, 2011, Baseline and projected future carbon storage and greenhouse-gas fluxes in the Great Plains region of the United States: U.S. Geological Survey Professional Paper 1787, 28 p. [Also available at http://pubs.usgs.gov/pp/1787/.]

Zhu, Zhiliang, and Reed, B.C., eds., 2012, Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of the Western United States: U.S. Geological Survey Professional Paper 1797, 192 p. [Also available at http://pubs.usgs.gov/pp/1797/.]

Zhu, Zhiliang, and Reed, B.C., eds., 2014, Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of the Eastern United States: U.S. Geological Survey Professional Paper 1804, 204 p. [Also available at http://dx.doi.org/10.3133/pp1804.]

Zhuang, Q., Melillo, J.M., Kicklighter, D.W., Prinn, R.G., McGuire, A.D., Steudler, P.A., Felzer, B.S., and Hu, S., 2004, Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century; A retrospective analysis with a process-based biogeochemistry model: Global Biogeochemical Cycles, v. 18, no. 3, article GB3010, 23 p., http://dx.doi.org/10.1029/2004GB002239.

Zhuang, Q., Melillo, J.M., McGuire, A.D., Kicklighter, D.W., Prinn, R.G., Steudler, P.A., Felzer, B.S., and Hu, S., 2007, Net emissions of CH_4 and CO_2 in Alaska; Implications for the region's greenhouse gas budget: Ecological Applications, v. 17, no. 1, p. 203–212, http://dx.doi.org/10.1890/1051-0761(2007)017[0203:NEOCAC]2.0.CO;2.