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Assessing historical and projected carbon balance of Alaska: A synthesis of results and policy/management implications

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Abstract. We summarize the results of a recent interagency assessment of land carbon dynamics in Alaska, in which carbon dynamics were estimated for all major terrestrial and aquatic ecosystems for the historical period (1950–2009) and a projection period (2010–2099). Between 1950 and 2009, upland and wetland (i.e., terrestrial) ecosystems of the state gained 0.4 Tg C/yr (0.1% of net primary production, NPP), resulting in a cumulative greenhouse gas radiative forcing of 1.68×10^{-3} W/m^2. The change in carbon storage is spatially variable with the region of the Northwest Boreal Landscape Conservation Cooperative (LCC) losing carbon because of fire disturbance. The combined carbon transport via various pathways through inland aquatic ecosystems of Alaska was estimated to be 41.3 Tg C/yr (17% of terrestrial NPP). During the projection period (2010–2099), carbon storage of terrestrial ecosystems of Alaska was projected to increase (22.5–70.0 Tg C/yr), primarily because of NPP increases of 10–30% associated with responses to rising atmospheric CO_2, increased nitrogen cycling, and longer growing seasons. Although carbon emissions to the atmosphere from wildfire and wetland CH_4 were projected to increase for all of the climate projections, the increases in NPP more than compensated for those losses at the statewide level. Carbon dynamics of terrestrial ecosystems continue to warm the climate for four of the six future projections and cool the climate for only one of the projections. The attribution analyses we conducted indicated that the response of NPP in terrestrial ecosystems to rising atmospheric CO_2 (~5% per 100 ppmv CO_2) saturates as CO_2 increases (between approximately +150 and +450 ppmv among projections). This response, along with the expectation that permafrost thaw would be much greater and release large quantities of permafrost carbon after 2100, suggests that projected carbon gains in terrestrial ecosystems of Alaska may not be sustained. From a national perspective, inclusion of all of Alaska in greenhouse gas inventory reports would ensure better accounting of the overall greenhouse gas balance of the nation and provide a foundation for considering mitigation activities in areas that are accessible enough to support substantive deployment.

Key words: Alaska; Alaska carbon cycle; boreal forest; climate change; fire; inland aquatic ecosystems; Landscape Conservation Cooperative; maritime conifer forest; permafrost; tundra; uplands; wetlands.

Introduction

Alaska occupies an area that is approximately one-fifth that of the conterminous United States. Ongoing warming in Alaska has the potential to substantially alter the exchange of carbon dioxide (CO_2) and methane (CH_4) between ecosystems and the atmosphere, and therefore the overall ecosystem carbon balance of Alaska (Striegl et al. 2007, Zhuang et al. 2007, Wolken et al. 2011, Yuan et al. 2012). Thus, the response of carbon dynamics to changes in climate and CO_2 concentrations in Alaska has implications for policies concerning the management of carbon in the United States. However, much of Alaska has not previously been included in any major national natural resource and

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greenhouse gas (GHG) inventory reports. The historical baseline carbon balance is poorly understood at a statewide level, and the potential for climate change to affect carbon dynamics in Alaska was not formally assessed until the U.S. Geological Survey Alaska Land Carbon Assessment (Zhu and McGuire 2016).

A major challenge in assessing carbon dynamics in Alaska is that the relative importance of driving forces that affect carbon storage varies regionally within Alaska (Wolken et al. 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 CO_2 and CH_4 between ecosystems and the atmosphere and (2) the overall ecosystem carbon balance (Kurz et al. 2008, McGuire et al. 2009, 2010, Hayes et al. 2011, 2012, 2014, Yuan et al. 2012). The maritime region of southern and southeastern Alaska features dense forest cover and active forest management (Wolken et al. 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 et al. 2006). To assess carbon dynamics of Alaska, it is important to implement methodologies capable of considering changes in major driving factors that influence carbon dynamics in its diverse ecosystems including Arctic tundra, alpine tundra, boreal forests, maritime forests, surface waters (rivers and lakes), and Arctic, boreal, and maritime wetlands.

While the carbon dynamics of Alaska have not been formally assessed, the historical carbon dynamics of ecosystems in Alaska have been studied at local, subregional, and regional scales. Some observational analyses 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. McGuire et al. (2012) suggested that Arctic tundra in Alaska was an annual source of CO_2 to the atmosphere between 1990 and 2009 of 10 ± 20 g C/m^2 and that the release of CO_2 in winter more than offset the uptake of CO_2 during the summer. Ueyama et al. (2013) evaluated factors influencing CO_2 exchange in eight Arctic tundra and five boreal ecosystems in Alaska 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 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. Several studies indicate that CO_2 losses from cold season respiration in recent years more than offset summer sinks in tundra ecosystems (Euskirchen et al. 2012, 2017, Belshe et al. 2013, Commane et al. 2017; Jeong et al., 2018). Fire disturbance has also been identified as an important factor that can affect carbon balance of tundra (Mack et al. 2011) and boreal forest (Hayes et al. 2011, Genet et al. 2017) ecosystems. Veraverbeke et al. (2015) estimated fire emission losses in Alaska of 15 Tg C/yr between 2001 and 2012.

Some analyses 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 limited to the 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 indicate that forest carbon stocks in southeast and south-central Alaska increased by ~6 ± 3 Tg (10^{12}) of carbon per year (Tg C/yr) between 1990 and 2013 (U.S. Department of Agriculture Forest Service 2015). In comparison, Genet et al. (2017) and Lyu et al. (2018) estimate that carbon storage in southeast and south-central Alaska increased 2.67 Tg C/yr in uplands and 0.07 Tg C/yr in lowlands, respectively, from 1950 to 2009. 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 of ~10 Tg C in the last few decades of the last century. However, it is not clear how well the methodology of Yarie and Billings (2002) accounts for carbon losses in fire emissions.

Previous research regarding carbon fluxes of rivers in Alaska has focused on the mainstream Yukon River and its tributaries, large rivers that drain the Arctic Slope, and small streams in southeast Alaska. The Yukon River total carbon exports have been estimated at ~8 Tg C/yr, with 70% of the total carbon flux as dissolved inorganic carbon (Striegl et al. 2007). Riverine CO_2 fluxes to the atmosphere have also been estimated at a similar magnitude in the Yukon River Basin (Striegl et al. 2012). Estimates of CO_2 emissions for other river systems and for lakes in Alaska have largely been reported as per area estimates (Cory et al. 2014, Hobbie and Kling 2014), as have carbon burial rates in lake sediments (Anderson et al. 2001, Lynch et al. 2002, Mann et al. 2002, Yu et al. 2008, Rogers et al. 2013). Thus, there is a need to scale data on carbon export, carbon exchange with the atmosphere, and carbon burial in a comprehensive and integrated fashion for inland aquatic ecosystems throughout the state.

A significant challenge is to develop a better budget of CH_4 exchange with the atmosphere in Alaska. Zhuang et al. (2007) estimated that combined emissions for Alaska between 1980 and 1996 were ~3 Tg CH_4/yr, which is somewhat higher than the estimate of ~2 Tg CH_4 growing season for Alaska based on data from an aircraft sampling campaign from 2012 to 2014 (Chang et al. 2014, Hartery et al. 2018). While it is encouraging that these estimates are in general agreement, there is a need to better partition CH_4 budgets in the state among CH_4 uptake by uplands and CH_4 emissions from wetlands and inland aquatic ecosystems.

This paper of the invited feature synthesizes the overall results from a recent collaborative and integrated Alaska carbon assessment (reported in Zhu and McGuire 2016) and the various components of the assessment including analysis of driving factors of carbon dynamics (Pastick et al. 2017), and syntheses of carbon dynamics across upland ecosystems (Genet et al. 2017), wetland ecosystems (Lyu et al. 2018), and inland aquatic ecosystems (Stackpoole et al. 2017) of Alaska. It is important to recognize that this assessment focused on carbon dynamics of Alaska ecosystems, and does not include an analysis of fossil fuel use and export by humans in Alaska. While the analyses presented in the invited feature are largely based on what was reported in Zhu and McGuire (2016), each of the papers in the invited feature includes additional analyses that were not included in that report. The carbon dynamics analyses of this synthesis were conducted for historical (1950–2009) and future projection (2010–2099) periods. In addition, we analyzed statewide cumulative GHG forcing across the combined historical and future projection periods. These analyses were broken down by landscape position (uplands vs. wetlands vs. inland aquatic ecosystems) where possible. The upland and wetland analyses were further broken down by regions of the landscape conservation cooperatives (LCCs) in Alaska: (1) the Arctic LCC, (2) the Western Alaska LCC, (3) the Northwest Boreal LCC, and (4) the North Pacific LCC (see Genet et al. 2017: Fig. 1). 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 (U.S. Fish and Wildlife Service 2010) to identify biologically cohesive areas to facilitate cooperative ecological management among local, state, and federal management agencies and stakeholders. The analyses of carbon dynamics for inland aquatic ecosystems were broken down by the six main hydrologic units of Alaska: the Arctic Slope, Northwest, Yukon, Southwest, South-Central, and Southeast Units (Seaber et al. 1987; see Stackpoole et al. 2017: Fig. 1). After discussion of the results of the assessment, we further discuss policy implications of the assessment and make recommendations for improving future assessments of carbon dynamics in Alaska.

Materials and Methods

General design of the Alaska land carbon assessment

The methodology developed for this assessment was designed to produce a scientific synthesis of carbon dynamics for Alaska 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 Alaska and technical components to make use of these data (Fig. 1). The key technical components included (1) the organization of input data for models and data syntheses; (2) modeling biogeography, fire regime, permafrost, and hydrologic dynamics; (3) biogeochemical modeling of carbon dynamics for upland and wetland ecosystems (collectively referred to as terrestrial ecosystems in this paper); and (4) data syntheses of carbon fluxes for inland aquatic ecosystems. We also conducted analyses of carbon dynamics for southeast Alaska based on forest inventory data available from the U.S. Forest Service; features of these analyses have been folded into the biogeochemical modeling of carbon dynamics for upland and wetland ecosystems (see Genet et al. 2017 and Lyu et al. 2018). The estimates of soil and vegetation carbon storage in this study were validated with data independent from those used in model development (see Genet et al. 2017 and Lyu et al. 2018).

Input data were organized for land-cover, wetland, inland aquatic ecosystem, and permafrost distributions; soil texture; soil carbon; vegetation carbon; upland and wetland biogeochemistry; historical and future climate and fire disturbance; historical forest harvest and mortality rates; and the transport, emission, and burial of aquatic carbon. The distribution of wetland and upland ecosystems in Alaska was defined by upscaling a random subset of the National Wetlands Inventory (see Pastick et al. 2017). The distribution of inland aquatic ecosystems in Alaska was defined from the National Hydrography Database (see Stackpoole et al. 2017). The historical and future climate and fire disturbance data sets, as well as data syntheses for permafrost distribution, are described in Pastick et al. (2017); analyses of biogeochemical cycling are described for uplands in Genet et al. (2017) and for wetlands in Lyu et al. (2018),

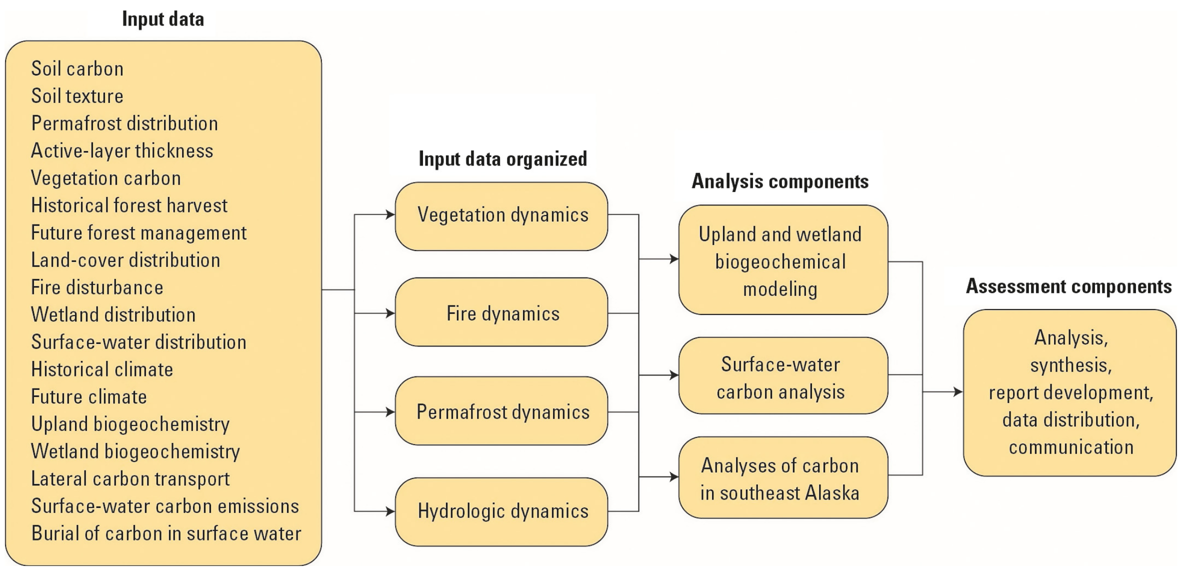

Fig. 1. Flowchart showing the general methodology used in the assessment of carbon storage and fluxes in Alaska. Input data were organized to provide information used to assess historical and future changes in vegetation, fire, permafrost, and hydrologic dynamics. The data on these changes were then 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).

and analyses of the transport, emission, and burial of aquatic carbon are described in Stackpoole et al. (2017).

Simulations by DOS-TEM were conducted across Alaska at a 1-km resolution from 1950 through 2099. DOS-TEM is driven by annual atmospheric CO_2 concentration, monthly mean air temperature, total precipitation, net incoming shortwave radiation, and vapor pressure. The atmospheric CO_2 and climate projections were aligned with the Intergovernmental Panel on Climate Change's Special Report on Emission Scenarios (IPCC-SRES; Nakićenović and Swart 2000). The assessment was driven by three CO_2 concentration trajectories associated with low-, mid-, and high-range CO_2 emission scenarios (A1B, A2, and B1, respectively). Before conducting the transient simulations, a typical spin-up procedure was conducted for each spatial location in which the model was driven by averaged modern forcings for climate and fire from year 1000 through 1900, repeated continuously until dynamic equilibrium of pools and fluxes was achieved at that location. The model was then run from 1901 through 1949 with historical climate for Alaska and averaged modern forcings for fire. The resulting modeled ecosystem state for each spatial location then served as the starting point for the transient simulation during the historical and future periods presented in this study.

To evaluate the effects of historical and projected climate warming, simulations were driven by output from two climate models for each of the three emission scenarios (B1, A1B, and A2; Nakićenović and Swart 2000). Between 2010 and 2099, the emission scenarios were characterized by increases in atmospheric CO_2 of 157 ppmv for B1, 318 ppmv for A1B, and 450 ppmv for A2. Each of the six future climate projections used the same downscaled historical climate data from 1901 through 2009 from the Climatic Research Unit (CRU TS 3.1; Harris et al. 2014). The climate projections were developed for 2010 through 2099 from the outputs of (1) version 3.1-T47 of the Coupled Global Climate Model (CCCMA, *available online*; McFarlane et al. 1992) developed by the Canadian Centre for Climate Modelling and Analysis and (2) version 5 of the European Centre Hamburg Model (ECHAM5, *available online*; Roeckner et al. 2004) developed by the Max Planck Institute.[15,16] For a given emission scenario, the climate projected by ECHAM5 tends to be warmer and drier than the climate projected by CCCMA (Zhu and McGuire 2016). For each climate model, the projected climate for the A2 emission scenario tends to be warmer than that for the A1B scenario, which tends to be warmer than that for the B1 scenario (Zhu and McGuire 2016). More details on the projected climates can be found in Pastick et al. (2017) and Genet et al. (2017).

The assessment uses the Alaska Frame-Based Ecosystem Code (ALFRESCO; Rupp et al. 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 Pastick et al. 2017 for more details). The contemporary spatial distribution of permafrost was estimated by two different empirical approaches. 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 et al. 2009a, b, 2010, Yuan et al. 2012, Genet et al. 2013). 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. The Methane Dynamics Module of the Terrestrial Ecosystem Model (MDM-TEM; Zhuang et al. 2004, 2007) was used to estimate methane consumption in upland ecosystems and both methane consumption and emissions in wetland ecosystems. A statewide map of lake area (U.S. Geological Survey 2012); modeled discharge, velocity, and width values for streams (Kost et al. 2002); carbon concentration in surface waters; and carbon burial rates in lakes was assimilated into empirical models to estimate regional and statewide estimates of carbon transport, emission, and burial in aquatic ecosystems of Alaska.

[15] www.cccma.ec.gc.ca/data/cgcm3/
[16] www.mpimet.mpg.de/en/wissenschaft/modelle/echam/

Estimates of changes in carbon stocks

Changes in carbon stocks were estimated for upland and wetland ecosystems, but not for inland aquatic ecosystems because of a lack of data on carbon stocks in Alaska. For the historical period, mean annual changes in vegetation and soil carbon stocks were calculated separately for uplands and wetlands by subtracting the area-weighted mean, in grams of carbon per square meter (g C/m^2), at the end of December 1949 from the area-weighted mean at the end of December 2009 and then dividing by 60 yr. The area-weighted means were obtained from the simulations conducted by DOS-TEM for uplands (Genet et al. 2017) and wetlands (Lyu et al. 2018). To convert to units of teragrams (10^{12} g) of carbon per year (Tg C/yr), the mean change in carbon stocks for uplands and wetlands was multiplied by the area in square meters (m^2) occupied by uplands (1.237774×10^{12} m^2) and wetlands (0.177069×10^{12} m^2). A similar procedure was followed for the projection period, except that the area-weighted mean for December 2009 was subtracted from the area-weighted mean for December 2099 and then divided by 90 yr.

Estimates of carbon fluxes

For uplands and wetlands, we report synthesis estimates of net primary productivity (NPP), heterotrophic respiration (HR), fire emissions (Fire), biogenic methane exchange ($BioCH_4$), and forest harvest (Harvest). Biogenic methane exchange was dominated by uptake of CH_4 from the atmosphere in uplands and by emissions of CH_4 to the atmosphere in wetlands. For the historical period, each mean annual carbon flux was separately calculated for uplands and wetlands by averaging the area-weighted mean flux in grams of carbon per square meter per year (g $C{\cdot}m^{-2}{\cdot}yr^{-1}$) from 1950 through 2009. The area-weighted means were obtained from the simulations conducted by DOS-TEM for uplands (Genet et al. 2017) and wetlands (Lyu et al. 2018). The mean flux was then multiplied by the respective area of uplands and wetlands (see above) to convert to units of Tg C/yr. A similar procedure was followed for the projection period, except that the area-weighted mean flux was averaged from 2010 through 2099. We calculated net ecosystem carbon balance (NECB; see Chapin et al. 2006) for upland and wetland ecosystems as follows:

$$NECB = NPP - HR - Fire - Harvest - BioCH_4. \quad (1)$$

For inland aquatic ecosystems, we report synthesis estimates of the export of carbon from rivers to the coastal ocean, the emission of CO_2 from rivers, the emission of CO_2 from lakes, and the burial of carbon in lakes. Estimates were obtained from Stackpoole et al. (2017) in Tg C/yr for the historical period. Stackpoole et al. (2017) did not make estimates of carbon fluxes for inland aquatic ecosystems for the future projection period.

Estimates of GHG radiative forcing 1950 through 2099

Estimates of GHG radiative forcing resulting from the fluxes of CH_4 and CO_2 were based on methods developed by Frolking et al. (2006) and Frolking and Roulet (2007). In the calculation, CH_4 emitted to the atmosphere was treated as a single reservoir with annual input and a first-order decay (reservoir mass divided by constant reservoir lifetime/adjustment time). CO_2 was simulated as a collection of five noninteracting reservoirs with different reservoir lifetimes. The input of each reservoir was a fraction of the annual flux, and the loss was determined by reservoir lifetime. The separate radiative forcings of CH_4 and CO_2 were calculated annually by multiplying the reservoir mass with the radiative forcing factor, respectively. The total GHG radiative forcing was then calculated by summing up the contributions of each individual gas in each year. In our analyses, we calculated GHG radiative forcing for seven spatial domains: (1) statewide, (2) wetlands, (3) uplands, (4) Arctic LCC, (5) Northwest Boreal LCC, (6) North Pacific LCC, and (7) Western Alaska LCC. Prior to 1950, we spun up the radiative forcing model to equilibrium using the mean 1901–1910 net CH_4 emissions (or uptake) from our simulations for the specific spatial domain with the assumption that the estimates of this time period were representative of long-term pre-1950 emissions (or uptake). We assumed that the pre-1950 CO_2 exchange was zero with the justification that, at larger spatial scales, CO_2 exchange across the landscape prior to changes in climate and disturbance regime since 1950 was largely characterized by a shifting mosaic of losses of CO_2 to the atmosphere (and CO, which is converted to CO_2 in the atmosphere on the order of months) associated with disturbance followed by CO_2 uptake associated with postdisturbance successional dynamics (see Grosse et al. 2011). These temporal patterns of losses and uptake in Alaska have been inferred based on chronosequence studies for wildfire disturbance in both uplands and wetlands (Turetsky et al. 2011, Yuan et al. 2012, Genet et al. 2013) and for thermokarst disturbance in wetlands (O'Donnell et al. 2012, Jones et al. 2017). It is also important to note that much of Alaska was unglaciated during the Pleistocene (Hamilton 1994, Briner and Kaufman 2008) and that many of the wetland complexes in the state were in existence during the Pleistocene.

Attribution analysis

The relative effect of increasing atmospheric CO_2, climate change, and increasing fire regime on ecosystem C balance was analyzed for the projection period (2010–2099), based on model simulations that included various combinations of time series for constant atmospheric CO_2, detrended climate variables, and normalized fire regime. For the constant CO_2 simulation, the atmospheric CO_2 of the baseline simulation was set at the 2009 concentration. The climate time series data were detrended for every 1-km pixel for each variable. A linear regression was fitted to the time series of mean air temperature, precipitation, shortwave incoming radiation, and vapor pressure. The detrended climate variables were then computed, as a function of the mean value of the variable for the last decade of the historical period 2000–2009, and the difference between the current and predicted variable.

The normalized fire regime data set was generated using a constant fire return interval (FRI) that was developed from the 1960–1989 fire records (Yuan et al. 2012). This scenario represents a constant fire frequency over time that reflects conditions prior to the significant increase of annual area burned observed in Alaska beginning in the 1990s. For each year, the group of pixels that were burned was randomly selected based on the last time they burned (in other words, the stand age) and the value of the FRI.

To determine the relative effects of rising atmospheric CO_2, changing climate, and fire regime, a set of ten statewide simulations was conducted from 2010 to 2099, in addition to the six statewide projections (i.e., CO_2 + climate + fire simulations). The baseline simulation combined constant atmospheric CO_2, detrended climate, and normalized fire regime. Three simulations combined the three scenarios of CO_2 emissions (B1, A1B, and A2) with detrended climate and normalized fire regime (CO_2 simulations). Finally, six simulations were conducted with rising atmospheric CO_2, and the six climate model scenarios and normalized fire regime (CO_2 + climate simulations). The effect of CO_2 fertilization was estimated by comparing baseline simulations with the CO_2 simulations. The effect of climate change was estimated by comparing decadal averages from the CO_2 simulations with the decadal averages from the CO_2 + climate simulations. Finally, the effect of a changing fire regime was estimated by comparing the CO_2 + climate simulations with the CO_2 + climate + fire simulations.

Results

Carbon dynamics and GHG radiative forcing in the historical period (1950–2009)

Soil carbon storage in Alaska terrestrial ecosystems in 1950 was estimated to be 52.1 Pg C with 47.1 Pg C stored in upland ecosystems. Vegetation carbon storage in 1950 was estimated to be 4.9 Pg C with 4.3 Pg C stored in upland ecosystems. The storage in upland ecosystems is greater because they occupy about 84% of the area (1.24 million km^2) in Alaska compared with wetland coverage of 12% (0.18 million km^2); inland aquatic ecosystems occupy 4% (0.06 million km^2) of Alaska.

Between 1950 and 2009, terrestrial ecosystems of Alaska were estimated to have gained an average of 0.4 Tg C/yr (26.8 loss to 4.1 gain Tg C/yr interannual variability), which is 0.1% of the mean annual NPP over the time period (Table 1, Fig. 2). This was largely because soil carbon gains (1.9 Tg C/yr) barely offset losses of vegetation carbon (−1.5 Tg C/yr). However, losses can be substantial during decades with substantial fire activity. For example, our simulations estimate that Alaska lost 10.6 Tg C/yr during the last decade of the historical period (2000–2009), largely as a result of extensive wildfire that occurred during that decade. Upland ecosystems of Alaska were primarily responsible for the gain in soil carbon (3.8 Tg C/yr) as wetland ecosystems were estimated to have lost soil carbon (−1.9 Tg C/yr). Vegetation carbon was estimated to have decreased in upland ecosystems at −0.6 Tg C/yr and in wetland ecosystems at −1.0 Tg C/yr, with substantial losses in the most recent decade of the historical period (Fig. 3a). Fire was the primary reason for the loss of vegetation carbon in the historical period, and most of the loss occurred in recent decades and in the Northwest Boreal LCC (Table 1; see also Genet et al. 2017 and Lyu et al. 2018). Although the Northwest Boreal LCC lost soil carbon because of fire, upland ecosystems of other LCCs were estimated to have gained soil carbon during the historical period.

The magnitude of NPP and HR in uplands was five to six times greater than that in wetlands, while the loss of carbon from wildfire was four times greater in uplands than in wetlands. Modeled forest harvest was entirely concentrated in uplands. It is important to note that harvested carbon was transferred/exported from live vegetation to an inert carbon pool (Fig. 2), and this pool did not contribute to our estimate of HR because we do not know when and where the carbon from harvested products is released. If we had considered the decomposition of harvested carbon in our analysis, it would have reduced the sink strength of terrestrial ecosystems of Alaska that we report. Modeled biogenic methane emissions for Alaska (0.90 Tg C/yr) were entirely concentrated in wetlands and were estimated to be 136 times estimated net biogenic CH_4 uptake in uplands. Our estimate of mean radiative forcing for the terrestrial component of Alaska from 1950 through 2009 (1.68×10^{-3} W/m^2; Fig. 4a) was dominated by CH_4 emissions in wetlands (1.83×10^{-3} W/m^2; Fig. 4b), particularly CH_4 emissions in the Northwest Boreal LCC (Table 1). In contrast to the carbon dynamics of wetlands, which acted to warm the atmosphere, we estimate that carbon dynamics of uplands acted to cool the atmosphere (-0.16×10^{-3} W/m^2; Fig. 4c) as uplands in three of the four LCCs stored carbon (Table 1); carbon balance in uplands of the Northwest Boreal LCC acted to warm the atmosphere (0.12×10^{-3} W/m^2) because of carbon losses caused by fire.

Inland aquatic ecosystems were estimated to have lost 41.3 Tg C/yr (5th and 95th percentiles of 30.4 Tg C/yr and 59.7 Tg C/yr) through export to the coast, CO_2 and CH_4 emissions from rivers and lakes, minus burial in lake sediments (Table 2, Fig. 2; Stackpoole et al. 2017), which is about 17% of NPP in terrestrial ecosystems. Our estimate of emissions of CH_4 from aquatic inland ecosystems (0.1 Tg C-CH_4/yr) was about an order of magnitude less than the estimate of CH_4 emissions from wetlands ecosystems (0.9 Tg C-CH_4/yr). Note that we do not report estimates of stock changes in inland aquatic ecosystems; because terrestrial and aquatic models were not integrated, terrestrial loading of carbon to aquatic ecosystems was not quantified. However, the sum of lateral export of carbon to

TABLE 1. Sixty-year carbon balance (Tg C/yr) of upland and wetland ecosystems in Alaska during the historical period (1950–2009).

Landform and LCC	Extent (km^2)	Delta VEGC†	Delta SOC‡	NPP§	HR¶	Pyrogenic CO + CO_2 emissions	Pyrogenic CH_4 emissions	Biogenic CH_4 emissions††	Timber exports	NECB‡‡
Wetland										
Arctic	29,818	0.12	0.35	4.03	−3.27	−0.22	−0.00	−0.08	−0.00	0.47
Northwest Boreal	130,704	−1.13	−2.36	28.81	−27.13	−4.36	−0.01	−0.79	−0.00	−3.49
North Pacific	1,965	0.00	0.06	0.53	−0.46	0.00	0.00	−0.00	−0.00	0.07
Western Alaska	14,582	0.03	0.02	2.95	−2.49	−0.37	−0.00	−0.04	−0.00	0.05
Statewide	177,069	−0.98	−1.93	36.32	−33.35	−4.96	−0.02	−0.91	−0.00	−2.91
Upland										
Arctic	261,481	0.82	2.34	28.68	−24.80	−0.71	−0.00	0.00	−0.00	3.16
Northwest Boreal	498,879	−2.05	−3.96	93.14	−86.57	−12.54	−0.04	0.00	−0.00	−6.01
North Pacific	150,087	0.03	2.64	24.23	−19.96	0.00	0.00	0.00	−1.60	2.67
Western Alaska	327,327	0.65	2.80	58.73	−48.90	−6.37	−0.02	0.00	−0.00	3.44
Statewide	1,237,774	−0.56	3.82	204.78	−180.23	−19.62	−0.06	0.01	−1.60	3.26
Alaska										
Arctic	291,299	0.94	2.69	32.71	−28.07	−0.93	−0.00	−0.08	−0.00	3.63
Northwest Boreal	629,583	−3.18	−6.32	121.95	−113.70	−16.90	−0.05	−0.79	−0.00	−9.50
North Pacific	152,052	0.03	2.70	24.76	−20.42	0.00	0.00	−0.00	−1.60	2.74
Western Alaska	341,909	0.68	2.82	61.68	−51.39	−6.74	−0.02	−0.04	−0.00	3.49
Statewide	1,414,843	−1.54	1.89	241.10	−213.58	−24.57	−0.08	−0.90	−1.60	0.35

†Change in vegetation carbon
‡Change in soil carbon (includes changes in coarse woody debris)
§Net primary production.
¶Heterotrophic respiration.
††Negative sign indicates net emissions, and positive sign indicates net uptake.
‡‡Net ecosystem carbon balance.

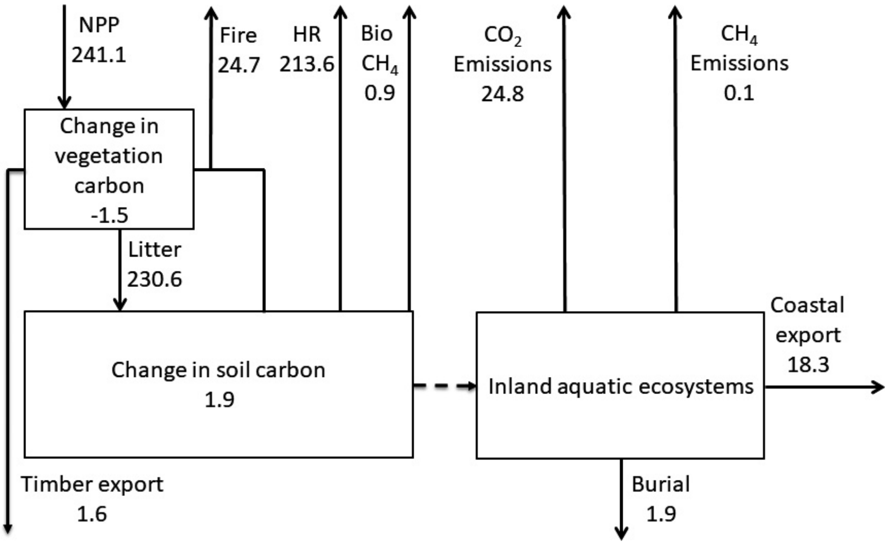

Fig. 2. The carbon balance of Alaska for the historical period (1950–2009) estimated for the terrestrial (upland and wetland) component (left) and the inland aquatic ecosystem component (right), in teragrams of carbon (10^{12} C) per year. The arrows indicate the direction of carbon flows between the pools (including the atmosphere [not shown]). Fluxes for the terrestrial component include net primary production (NPP), heterotrophic respiration (HR), fire emissions (including pyrogenic CH_4 emissions), biogenic CH_4 emissions (Bio. CH_4), and the litterfall flux of carbon, which is provided in this figure to provide information relevant to the mass balance of terrestrial soil carbon. The flux of carbon from terrestrial vegetation and soil to the inland aquatic ecosystem component (represented by the dashed arrow) was not explicitly estimated.

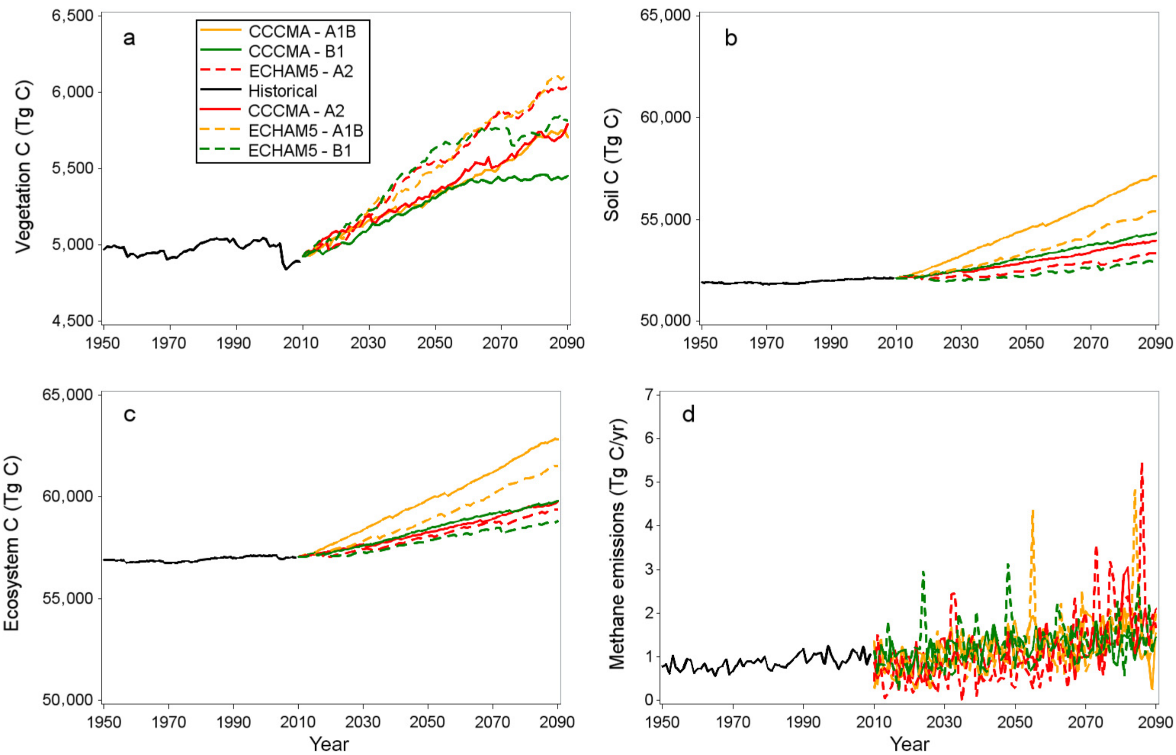

Fig. 3. Time series of statewide carbon dynamics for Alaska for the historical (1950–2009) and projected (2010–2099) periods for (a) vegetation carbon, (b) soil carbon, (c) total ecosystem carbon, and (d) net methane emissions to the atmosphere.

Alaska coasts and carbon emissions across water surfaces is significant. These results suggest that when the lateral export from terrestrial ecosystems and processing and removal of carbon through inland aquatic ecosystems are properly taken into account, the calculated capacity of soil and vegetation to store carbon and the heterotrophic respiration estimates for uplands and wetlands (Table 1) may be reduced.

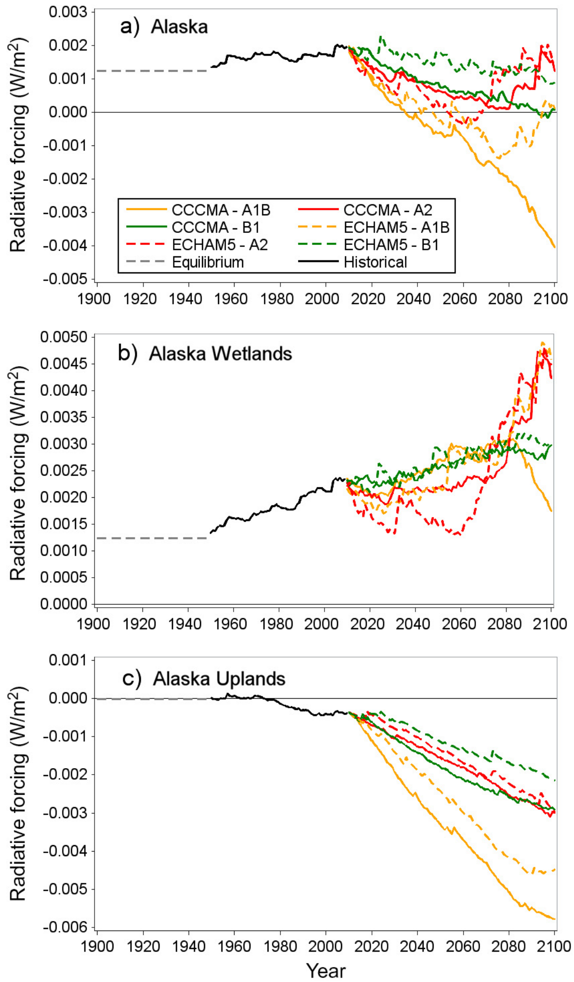

FIG. 4. Estimated radiative forcing from 1950 through 2099 for (a) combined wetland and upland terrestrial ecosystems of Alaska, (b) wetland ecosystems of Alaska, and (c) upland ecosystems of Alaska.

Projected carbon dynamics for the future period (2010–2099)

Our analysis of future estimated carbon dynamics of Alaska (2010–2099) only considered the effects of future climate projections on carbon dynamics in terrestrial ecosystems. The simulations indicated that carbon storage in terrestrial ecosystems would substantially increase across all six future climate simulations (Fig. 3). Estimates of changes in carbon storage (NECB in Table 3) range from 22.5 Tg C/yr under ECHAM5 B1 climate to 70.0 Tg C/yr under CCCMA A1B climate; these estimates are substantially greater than the estimate of NECB for the historical period (0.4 Tg C/yr; Table 1). The transition in carbon accumulation is generally smooth between the historical and projected periods (Fig. 3a–c), except perhaps for soil carbon accumulation for the CCCMA A1B climate. In the first decade of the projected period (2010–2019), our simulations indicated losses of ~4 Tg C/yr in total ecosystem carbon storage for the ECHAM5 A2 and B1 climates, and gains of between 3.7 and 22.2 Tg C/yr among the other four projected climates. The losses for the two ECHAM5 climates occurred largely because estimates of statewide HR and fire emission losses were substantially higher than those for the CCCMA climates. Uplands were responsible for 86–95% of estimated NECB among the simulations for future climate projections. Together, the Northwest Boreal and Western Alaska LCCs dominated the statewide NECB; the Northwest Boreal LCC had the highest estimated NECB among the LCCs for four of the six future climate projections.

The projected increases in carbon storage were driven by both increases in NPP of between 10% (CCCMA B1) and 30% (ECHAM5 A1B) and decreases in HR of up to 21% (CCCMA A1B). Projected change in fire emissions across the projected climate simulations varied from a 21% increase (CCCMA A1B) to a 155% increase (ECHAM5 A1B). The decreases in HR primarily occurred because increased fire in the Northwest Boreal LCC caused a substantial decrease in HR in that region associated with large losses of soil carbon in fire that decreased HR more than increased soil temperature increased HR (see Genet et al. 2017). In other LCC regions, HR generally increased in the future because of warmer soils.

Biogenic CH_4 emissions were estimated to be between 1.22 (CCCMA A1B) and 1.43 (ECHAM5 A1B) Tg C-CH_4/yr among the simulations for the future climate projections, which represents a 36% to 59% increase in comparison with the estimate for the historical period. As for the simulation for the historical period, the Northwest Boreal LCC dominated the estimates of biogenic CH_4 emissions for the future climate projections.

GHG radiative forcing 2010 through 2099

Our simulations estimate that statewide GHG radiative forcing was 1.68×10^{-3} W/m^2 during the historical period (Fig. 4a) and ranged between -0.84×10^{-3} W/m^2 (CCCMA A1B) and 1.50×10^{-3} W/m^2 (ECHAM5 B1) among the six climate projections. At the statewide level, the warming effect of net CH_4 emissions offset the cooling effect of net CO_2 uptake in for four of six climate projections (Fig. 4a); GHG radiative forcing was essentially zero for the ECHAM5 A1B climate projection and was substantially negative for only the CCCMA A1B climate projection, which had the largest carbon gain at the statewide level among the projections (Table 3). During the projected period, the trajectory of GHG radiative forcing depended on the climate projection (Fig. 4a).

TABLE 2. Sixty-year carbon balance (Tg C/yr) of inland aquatic ecosystems in Alaska during the historical period (1950–2009).

Parameter	Coastal carbon export from river ecosystems	Carbon dioxide emissions from river ecosystems	Carbon dioxide emissions from lake ecosystems	Methane emissions from river and lake ecosystems	Carbon burial in lake ecosystems	Total flux from inland aquatic ecosystems
Total	18.3	16.6	8.2	0.1	1.9	41.3

TABLE 3. Projected carbon balance (Tg C/yr) of upland and wetland ecosystems in Alaska for the projection period (2010–2099).

Landform, LCC, and climate projection	Delta VEGC†	Delta SOC‡	NPP§	HR¶	Pyrogenic CO + CO_2 emissions	Pyrogenic CH_4 emissions††	Biogenic CH_4 emissions††	NECB‡‡
Wetland								
Arctic								
CCCMA A1b	0.16	1.32	5.36	−3.20	−0.59	−0.00	−0.09	1.48
CCCMA A2	0.12	0.92	5.50	−2.71	−1.65	−0.00	−0.09	1.04
CCCMA B1	0.11	0.51	5.46	−4.23	−0.54	−0.01	−0.07	0.62
ECHAM5 A1B	0.17	0.82	6.42	−3.58	−1.75	−0.03	−0.10	0.98
ECHAM5 A2	0.21	0.86	5.97	−3.03	−1.77	−0.04	−0.10	1.07
ECHAM5 B1	0.12	0.85	5.68	−3.34	−1.29	−0.02	−0.08	0.97
Northwest Boreal								
CCCMA A1B	1.58	−0.46	30.94	−22.05	−6.67	−0.06	−1.08	1.12
CCCMA A2	1.53	1.43	30.63	−19.34	−7.04	−0.08	−1.27	2.95
CCCMA B1	1.13	−0.34	30.06	−21.58	−6.48	−0.07	−1.19	0.79
ECHAM5 A1B	1.90	−0.33	33.33	−23.24	−7.22	−0.07	−1.27	1.58
ECHAM5 A2	1.98	0.56	33.04	−23.48	−5.85	−0.07	−1.15	2.54
ECHAM5 B1	1.63	0.19	31.89	−23.51	−5.29	−0.05	−1.24	1.83
North Pacific								
CCCMA A1B	0.04	0.23	0.62	−0.33	−0.01	−0.00	−0.01	0.27
CCCMA A2	0.05	0.08	0.65	−0.46	−0.06	−0.00	−0.01	0.12
CCCMA B1	0.04	0.10	0.62	−0.48	−0.01	−0.00	−0.00	0.13
ECHAM5 A1b	0.05	0.18	0.72	−0.41	−0.07	−0.01	−0.01	0.23
ECHAM5 A2	0.05	0.03	0.62	−0.49	−0.05	−0.01	−0.01	0.08
ECHAM5 B1	0.04	0.07	0.65	−0.48	−0.07	−0.01	−0.00	0.11
Western Alaska								
CCCMA A1B	0.05	0.79	3.25	−2.07	−0.29	−0.01	−0.05	0.84
CCCMA A2	0.06	0.24	3.25	−2.14	−0.75	−0.05	−0.05	0.30
CCCMA B1	0.00	0.48	3.18	−1.99	−0.67	−0.03	−0.04	0.48
ECHAM5 A1B	0.09	−0.09	3.90	−3.05	−0.78	−0.06	−0.06	0.01
ECHAM5 A2	0.11	0.28	3.55	−2.44	−0.67	−0.05	−0.06	0.39
ECHAM5 B1	0.08	0.05	3.43	−2.71	−0.54	−0.04	−0.04	0.13
Statewide								
CCCMA A1B	1.83	1.88	40.17	−27.65	−7.56	−0.07	−1.23	3.71
CCCMA A2	1.75	2.67	40.02	−24.65	−9.51	−0.16	−1.42	4.42
CCCMA B1	1.28	0.75	39.33	−28.29	−7.69	−0.11	−1.30	2.02
ECHAM5 A1B	2.21	0.59	44.37	−30.29	−9.82	−0.18	−1.44	2.80
ECHAM5 A2	2.35	1.73	43.20	−29.43	−8.34	−0.16	−1.31	4.08
ECHAM5 B1	1.87	1.16	41.65	−30.04	−7.19	−0.12	−1.36	3.03
Upland								
Arctic								
CCCMA A1B	0.88	6.77	35.80	−26.92	−1.22	−0.00	0.00	7.66
CCCMA A2	0.72	4.22	37.05	−23.62	−8.45	−0.03	0.00	4.95
CCCMA B1	0.68	1.14	36.71	−33.18	−1.70	−0.01	0.00	1.82
ECHAM5 A1B	1.26	2.99	43.83	−29.32	−10.22	−0.03	0.00	4.25
ECHAM5 A2	1.48	3.96	41.19	−24.79	−10.93	−0.04	0.00	5.44
ECHAM5 B1	0.83	3.55	38.63	−27.41	−6.81	−0.02	0.00	4.38
Northwest Boreal								
CCCMA A1B	3.01	14.38	28.83	−21.21	−16.55	−0.05	0.00	17.39
CCCMA A2	2.72	9.29	29.24	−22.39	−23.58	−0.08	0.00	12.01
CCCMA B1	1.98	4.51	28.02	−22.46	−22.11	−0.07	0.00	6.48
ECHAM5 A1B	4.00	14.54	33.47	−25.83	−21.54	−0.07	0.00	18.54
ECHAM5 A2	4.19	5.84	28.68	−23.57	−20.82	−0.07	0.00	10.04
ECHAM5 B1	3.32	5.65	29.74	−23.61	−15.45	−0.05	0.00	8.97
North Pacific								
CCCMA A1B	2.49	5.00	97.47	−63.47	−0.13	−0.00	0.00	7.49
CCCMA A2	2.81	2.02	96.30	−60.64	−2.00	−0.01	0.00	4.84
CCCMA B1	1.92	3.57	95.12	−66.45	−0.07	−0.00	0.00	5.49
ECHAM5 A1B	3.05	1.07	106.33	−66.18	−3.50	−0.01	0.00	4.12
ECHAM5 A2	2.68	0.61	104.15	−73.23	−1.81	−0.01	0.00	3.30
ECHAM5 B1	2.19	1.43	100.95	−76.48	−2.51	−0.01	0.00	3.62

TABLE 3. (Continued)

Landform, LCC, and climate projection	Delta VEGC†	Delta SOC‡	NPP§	HR¶	Pyrogenic CO + CO_2 emissions	Pyrogenic CH_4 emissions††	Biogenic CH_4 emissions††	NECB‡‡
Western Alaska								
CCCMA A1B	1.97	31.74	66.77	−28.93	−4.12	−0.01	0.00	33.71
CCCMA A2	1.80	4.08	67.64	−46.34	−15.37	−0.05	0.00	5.88
CCCMA B1	0.91	16.07	65.68	−40.51	−8.17	−0.03	0.00	16.98
ECHAM5 A1B	2.67	17.18	85.22	−47.79	−17.52	−0.06	0.00	19.86
ECHAM5 A2	2.90	4.91	74.07	−51.81	−14.40	−0.06	0.00	7.81
ECHAM5 B1	1.91	0.58	70.83	−56.77	−11.52	−0.04	0.00	2.50
Statewide								
CCCMA A1B	8.36	57.89	228.87	−140.53	−22.01	−0.07	0.01	66.25
CCCMA A2	8.04	19.62	230.22	−152.99	−49.41	−0.16	0.01	27.66
CCCMA B1	5.48	25.29	225.52	−162.60	−32.05	−0.11	0.01	30.77
ECHAM5 A1B	10.99	35.79	268.84	−169.11	−52.78	−0.17	0.01	46.77
ECHAM5 A2	11.25	15.33	248.08	−173.39	−47.95	−0.16	0.01	26.58
ECHAM5 B1	8.26	11.21	240.14	−184.27	−36.28	−0.12	0.01	19.47
Alaska								
Arctic								
CCCMA A1B	1.04	8.09	41.16	−30.12	−1.81	−0.00	−0.09	9.14
CCCMA A2	0.84	5.14	42.55	−26.33	−10.11	−0.06	−0.09	5.99
CCCMA B1	0.79	1.65	42.17	−37.41	−2.24	−0.02	−0.07	2.44
ECHAM5 A1B	1.43	3.81	50.25	−32.90	−11.97	−0.06	−0.10	5.23
ECHAM5 A2	1.69	4.82	47.16	−27.82	−12.70	−0.08	−0.10	6.51
ECHAM5 B1	0.95	4.40	44.31	−30.75	−8.10	−0.04	−0.08	5.35
Northwest Boreal								
CCCMA A1B	4.59	13.92	59.77	−43.26	−23.22	−0.11	−1.08	18.51
CCCMA A2	4.25	10.72	59.87	−41.73	−30.62	−0.16	−1.27	14.96
CCCMA B1	3.11	4.17	58.08	−44.04	−28.58	−0.14	−1.19	7.27
ECHAM5 A1B	5.90	14.21	66.80	−49.07	−28.76	−0.14	−1.27	20.12
ECHAM5 A2	6.17	6.40	61.72	−47.05	−26.67	−0.14	−1.15	12.58
ECHAM5 B1	4.95	5.84	61.63	−47.12	−20.74	−0.10	−1.24	10.80
North Pacific								
CCCMA A1B	2.53	5.23	98.09	−63.80	−0.14	−0.00	−0.01	7.76
CCCMA A2	2.86	2.10	96.95	−61.10	−2.06	−0.01	−0.01	4.96
CCCMA B1	1.96	3.67	95.74	−66.93	−0.07	−0.00	−0.00	5.62
ECHAM5 A1B	3.10	1.25	107.05	−66.59	−3.57	−0.02	−0.01	4.35
ECHAM5 A2	2.73	0.64	104.77	−73.72	−1.86	−0.02	−0.01	3.38
ECHAM5 B1	2.23	1.50	101.60	−76.96	−2.58	−0.02	0.00	3.73
Western Alaska								
CCCMA A1B	2.02	32.53	70.02	−31.00	−4.40	−0.02	−0.05	34.55
CCCMA A2	1.86	4.32	70.89	−48.48	−16.13	−0.10	−0.05	6.18
CCCMA B1	0.91	16.55	68.86	−42.50	−8.84	−0.06	−0.04	17.46
ECHAM5 A1B	2.76	17.09	89.12	−50.84	−18.30	−0.12	−0.06	19.87
ECHAM5 A2	3.01	5.19	77.62	−54.25	−15.07	−0.10	−0.06	8.20
ECHAM5 B1	1.99	0.63	74.26	−59.48	−12.06	−0.08	−0.04	2.63
Statewide								
CCCMA A1B	10.19	59.77	269.04	−168.18	−29.57	−0.14	−1.22	69.96
CCCMA A2	9.79	22.29	270.24	−177.64	−58.92	−0.32	−1.41	32.08
CCCMA B1	6.76	26.04	264.85	−190.89	−39.74	−0.22	−1.29	32.79
ECHAM5 A1B	13.20	36.38	313.21	−199.40	−62.60	−0.35	−1.43	49.57
ECHAM5 A2	13.60	17.06	291.28	−202.82	−56.30	−0.32	−1.30	30.66
ECHAM5 B1	10.13	12.37	281.79	−214.31	−43.47	−0.24	−1.35	22.50

Note: LCC, Landscape Conservation Cooperative region.
†Change in vegetation carbon.
‡Change in soil carbon.
§Net primary production.
¶Heterotrophic respiration.
††Negative sign indicates net emissions, and positive sign indicates net uptake.
‡‡Net ecosystem carbon balance.

For wetlands, our simulations estimate that GHG radiative forcing was 1.84×10^{-3} W/m^2 during the historical period (Fig. 4b) and ranged between 2.33×10^{-3} W/m^2 (ECHAM5 A2) and 2.67×10^{-3} W/m^2 (ECHAM5 B1) among the six climate projections, an increase of ~25% to 50%. For uplands, our simulations estimate that GHG radiative forcing was -0.16×10^{-3} W/m^2 during the historical period (Fig. 4c) and ranged between -1.17×10^{-3} W/m^2 (ECHAM5 B1) and -3.34×10^{-3} W/m^2 (CCCMA A1B), an 8- to 21-fold increase. The GHG radiative forcing in uplands was most negative for the A1B climates (Fig. 4c), which explains why our simulations indicated that these climate scenarios would not act to warm the climate at the statewide level (Fig. 4a).

Estimated GHG radiative forcing from 1950 through 2099 was negative for historical climate and decreased for all climates in the Arctic (Fig. 5a), North Pacific (Fig. 5c), and Western Alaska (Fig. 5d) LCCs, but was positive for the historical and all future climates in the Northwest Boreal LCC (Fig. 5b). The strongest decreases in the Arctic, North Pacific, and Western Alaska LCCs were for the CCCMA A1B climate, for which the Northwest Boreal LCC also showed a decrease between 2080 and 2099.

Discussion

Alaska spans a broad range in climate from the maritime coastal regions of south-central and southeast Alaska to the boreal forest region in interior Alaska to arctic and maritime tundra regions of northern and western Alaska. The environmental conditions of Alaska have led to the storage of vast quantities of soil and biomass carbon. Although forest ecosystems of southeast Alaska have been regularly included in national resource or greenhouse gas inventory programs, other regions of Alaska have not been included in national-level resource or greenhouse gas inventory programs because these areas were designated "unmanaged" according to reporting guidelines by the Intergovernmental Panel on Climate Change (IPCC 2006), due to the lack of extensive transportation infrastructure and the low density of field data to support such programs. Yet, high-latitude ecosystems are potentially very vulnerable to climate change during the remainder of the century because temperature is projected to increase substantially more in boreal and arctic regions than in regions closer to the equator. In particular, these increases in temperature may expose the substantial stores of carbon in the region to loss from more wildfire and permafrost thaw, which could turn the ecosystems of Alaska into a net carbon source. Therefore, the assessment of Alaska ecosystem carbon stocks and fluxes as well as methane fluxes, as reported here, was conducted to better understand the baseline and projected carbon distributions and potential responses to a rapidly changing environment. Below, we first discuss the findings of this assessment for historical carbon dynamics, future carbon dynamics, and GHG radiative forcing of ecosystems in Alaska. We then discuss the policy implications of these findings. Finally, we conclude this discussion by making recommendations for future assessments of carbon dynamics in Alaska.

Carbon dynamics in the historical period (1950–2009)

Our analyses indicate that between 1950 and 2009, upland and wetland ecosystems of Alaska were a very weak sink for atmospheric carbon (0.4 Tg C/yr). However,

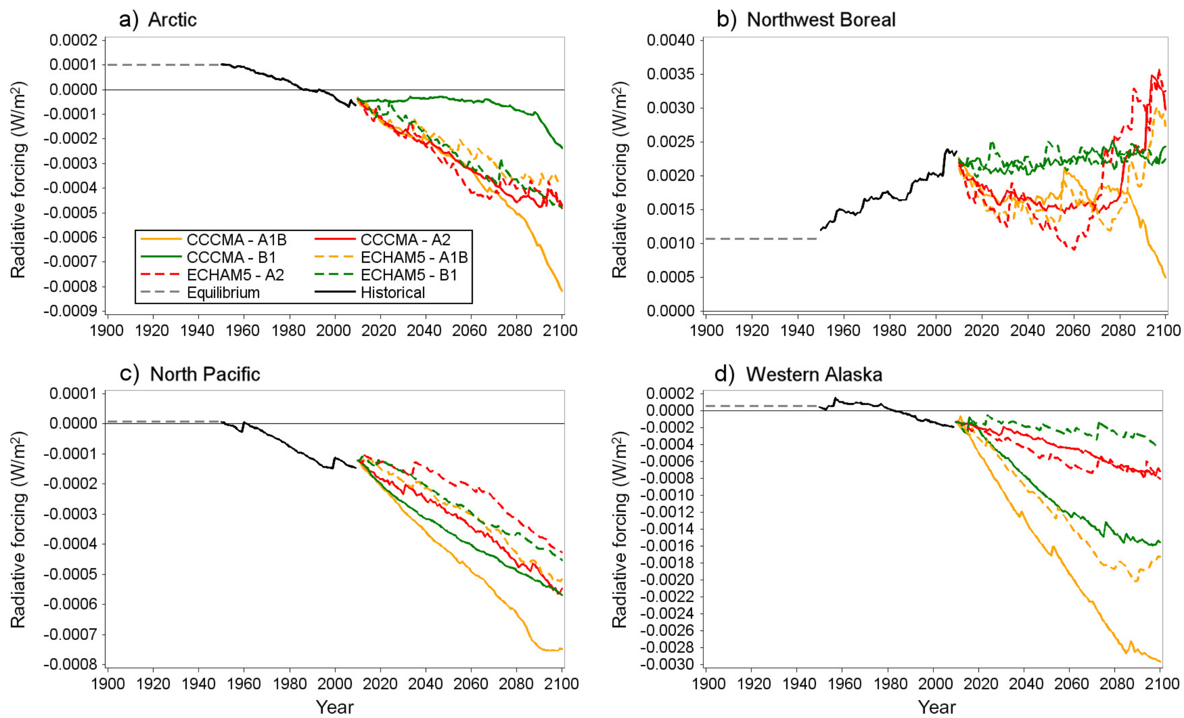

Fig. 5. Estimated radiative forcing in Alaska from 1950 through 2099 for (a) the Arctic Landscape Conservation Cooperative (LCC) region, (b) the Northwest Boreal LCC region, (c) the North Pacific LCC region, and (d) the Western Alaska LCC region.

different regions of Alaska acted as either strong sources (−9.5 Tg C/yr in the Northwest Boreal LCC) or moderate sinks (2–4 Tg C/yr in each of the other LCCs). The loss of carbon in the Northwest Boreal LCC highlights the vulnerability of this region to changes in fire regime, which changed from one to two large fire years per decade in the early part of the historical period to three to four large fire years per decade in the later part (Kasischke et al. 2010). Fire losses in Alaska during large fire years can be substantial (Veraverbeke et al. 2015, 2017), and our simulations indicate that these losses were particularly high in the last decade of the historical period. In addition, several analyses suggest that productivity in boreal forest regions has decreased in recent decades (Beck and Goetz 2011). The sinks in the two tundra regions of Alaska are consistent with the inference from analyses of satellite data that carbon uptake in tundra has increased in recent decades (Frost and Epstein 2014, Ju and Masek 2016), although some recent studies indicate that the long-term trend of greening in tundra may be experiencing a reversal in this decade (Epstein et al. 2015, Phoenix and Bjerke 2016). Also, there are several studies that suggest that the Arctic LCC region of Alaska may now be a source of CO_2 to the atmosphere because of cold season respiration that more than offsets summer uptake of C (Euskirchen et al. 2012, 2017, Belshe et al. 2013, Commane et al. 2017; Jeong et al., 2018). An increase in carbon storage in the maritime forest region of Alaska during recent decades has been estimated using forest inventory data from the region (U.S. Department of Agriculture Forest Service 2015).

Our analyses in this assessment also indicate that inland aquatic ecosystems have lost 43.1 Tg C/yr through several pathways. It is important to recognize that the methodology applied in this assessment does not allow us to simply combine the estimated carbon balance of upland and wetland ecosystems with that of inland aquatic ecosystems over the historical period. Thus, it is not clear whether ecosystems in Alaska have gained carbon in the historical period or whether they have lost carbon. The key methodological uncertainties concern (1) the heterotrophic respiration flux from upland and wetland ecosystems and (2) the flux of carbon from terrestrial to inland aquatic ecosystems (Fig. 2). The heterotrophic respiration estimate (213.6 Tg C/yr) is likely an overestimate in the context of the modeling framework because the DOS-TEM model does not represent losses to inland aquatic ecosystems. If the estimated heterotrophic respiration flux were reduced by an amount to balance the carbon budget of inland aquatic ecosystems, then the carbon balance for Alaska during the historical period would be equivalent to the total NECB of terrestrial ecosystems (carbon gain of 0.4 Tg C/yr). Clearly, it is important to treat the carbon dynamics of upland, wetland, and aquatic ecosystems as an integrated system to better estimate the net carbon balance of Alaska.

The estimates of soil and vegetation carbon storage in this study were validated with data independent from those used in model development (Genet et al. 2017, Lyu et al. 2018). The evaluation of the soil carbon estimates of DOS-TEM generally indicated good agreement with other reported estimates for Alaska (Zhu and McGuire 2016). There were no independent estimates of vegetation carbon storage at the statewide level against which to compare the vegetation carbon estimates of this assessment. The large-scale flux estimates of the historical period are difficult to evaluate with existing independent analyses, because these analyses are restricted in spatial and temporal scope. For example, the synthesis of eddy covariance data in Alaska by Ueyama et al. (2013) found that all five of the boreal and seven of the eight arctic tundra ecosystems analyzed acted as CO_2 sinks during the growing season. Our results for the historical period of mature undisturbed ecosystems of Alaska are certainly consistent with this result, but the study of Ueyama et al. (2013) does not provide a quantitative means of evaluating our simulations at the statewide scale and across the 60 yr of the historical period. Also, the estimates of Ueyama et al. (2013) are relevant to only the growing season, and it is necessary to know how respiratory losses outside the growing season influence the full annual balance (Euskirchen et al. 2012, 2017, Belshe et al. 2013, Commane et al. 2017; Jeong et al., 2018). Another analysis based on atmospheric CO_2 data indicates that tundra regions of Alaska are sources of CO_2 to the atmosphere from 2012 through 2014, which does not overlap our historical period, because of increasing early winter season respiration fluxes that have been estimated to have increased by 73% since 1975 (Commane et al. 2017). In contrast, our simulations estimate that early winter season respiration fluxes in tundra regions have increased by 13% since 1975, which is much less than estimated by Commane et al. (2017). Although the increase in HR for tundra regions of Alaska may be underestimated in our simulations compared to that estimated by Commane et al. (2017), the simulations for the warmer ECHAM5 climate projections for the decade of 2010–2019 have higher HR losses than those for the CCCMA climate projections. Our estimate of net CH_4 emissions for Alaska (from fire, wetlands, river, and lakes minus upland uptake) for the historical period of 1.1 Tg C/yr (1.5 Tg CH_4/yr) is substantially less than the mean growing season estimate of 1.6 Tg C/yr (2.1 Tg CH_4/yr) for Alaska based on data from an aircraft sampling campaign conducted between 2012 and 2014 (Chang et al. 2014, Hartery et al. 2018). Although the difference in magnitude between the two estimates may, in part, be the result of problems in comparing a long-term mean to an estimate based on three years of data, we suspect that the area occupied by wetlands in our analyses could be biased low as the application of the same methane dynamics model we used in this assessment estimated 3.1 Tg CH_4/yr for a different wetland land-cover map over the time period 1980 through 1996 (Zhuang et al. 2007). In conclusion, although the observational data on carbon dynamics in Alaska do not yet provide enough information for fully evaluating the exchange of GHGs estimated by the process-based models used in this assessment, the observational information is useful at this point in time for some first-order evaluation of the magnitude and seasonality simulated by process-based models.

Projected carbon dynamics for the future period (2010–2099)

In contrast to the historical period, our analysis of carbon dynamics in the projection period (2010–2099) indicates that carbon storage of upland and wetland ecosystems of

Alaska would increase substantially (22.5–70.0 Tg C/yr). This largely occurs because of increases in NPP between 10 and 30% and decreases in HR up to 21% at the statewide level. The attribution analyses of these responses by Genet et al. (2017) and Lyu et al. (2018) indicate that NPP increases primarily because of its sensitivity to increases in atmospheric CO_2 and temperature (~5% per 100 ppmv and ~3.0% per °C increase at statewide level, respectively); among projections, atmospheric CO_2 increased between +150 and +450 ppmv and statewide air temperature increased between +1.8°C and +4.8°C. The sensitivity of NPP to changes in atmospheric CO_2 is substantially lower than the estimates from four free air carbon dioxide enrichment (FACE) experiments in temperate forest stands (13% per 100 ppm; Norby et al. 2005) and in comparison with most other models applied over the northern permafrost region (McGuire et al. 2016) because of nitrogen limitation on the CO_2 fertilization response in DOS-TEM. The sensitivity of NPP to increases in temperature is interpreted due to increased nitrogen cycling and longer growing seasons and is generally consistent with past warming experiments conducted in arctic Alaska (Chapin et al. 1995, Piao et al. 2013).

Although carbon emissions to the atmosphere from wildfire were projected to increase substantially for all climate simulations, the statewide increases in NPP more than compensated for those region-specific losses. The increases in wildfire, primarily in the Northwest Boreal and Western Alaska LCCs, were also responsible for the statewide decreases in HR that occurred in five of the six future climate simulations. The decrease in HR following wildfire is related to the partial or total burning of the organic horizons during combustion and the subsequent decrease in carbon input from vegetation litterfall during early phases of secondary succession (Genet et al. 2017). It should be noted that our simulations with DOS-TEM reported here did not model future forest harvest in southeast Alaska. A business-as-usual forest harvest similar to what we considered for the historical analysis for southeast Alaska would likely translate to an ~1.6 Tg C/yr decrease in NECB, and therefore would have little effect on the projected increases in NECB we estimate.

Our simulations for the future climate projections indicated that biogenic methane emissions increased 36% to 59% in comparison with the estimate for the historical period. The attribution analysis conducted by Lyu et al. (2018) indicated that increases in biogenic CH_4 were primarily driven by increases in air temperature (~15% per °C increase). The positive response of CH_4 emissions to increasing air temperature is in agreement with short-term CH_4 observations in boreal and Arctic regions (Olefeldt et al. 2013). The long-term response of CH_4 emissions to climate change in our simulations is somewhat greater than the 7–35% projected increases under climate projections in the northern permafrost region considered by Koven et al. (2015) for the time period from 2010 through 2100.

GHG radiative forcing 2010 through 2099

Although we estimate that carbon stocks slightly increased during the historical period, our analysis of GHG radiative forcing indicates that upland and wetland ecosystems of Alaska acted to warm the climate (1.68×10^{-3} W/m^2) because of methane emissions to the atmosphere. Our analysis of GHG radiative forcing indicates that Alaska would continue to warm the climate for four of the six climate projections we considered during the 2010–2099 time period, would neither warm nor cool the climate for the ECHAM5 A1B climate projection, and would act to cool the climate for the CCCMA A1B climate projection. This largely depended on the relative strength of net CO_2 uptake in the future, as the range of the relative increase in biogenic methane emissions during the projection period (increase of 36–59% over the historical rate) was much smaller than the relative increase in net CO_2 uptake (64–200 times over the historical rate) across the future climate projections. The GHG radiative forcing was greatest for the ECHAM5 B1 climate projection because it had both the most positive forcing associated with CH_4 emissions in wetlands and the least negative forcing associated with CO_2 uptake in uplands; among the climate projections, the simulation for the ECHAM5 B1 climate resulted in the least amount of carbon gain. In contrast, carbon gain increased the most for the CCCMA A1B climate projection, which resulted in the GHG radiative forcing cooling the climate over the remainder of this century in our simulations. Finally, the estimates of cumulative GHG radiative forcing depend on the relative responses in different LCCs, as carbon dynamics in the Northwest Boreal LCC would warm the climate for all projections while carbon dynamics in the other LCCs would cool the climate for all projections.

Policy and management implications

The results of this assessment have implications for carbon management strategies that might be implemented as part of national policies aimed at maintaining the functions of ecosystems in removing greenhouse gases from the atmosphere and controlling the rate and overall magnitude of climate change. Despite the major advance in assessing the Alaska carbon budget, there remain significant uncertainties in the direction and magnitude of fluxes, partitioning of estimated fluxes among ecosystems, and lack of full attribution to natural and anthropogenic drivers. Uncertainties in model projections make it difficult to predict how different management activities might affect radiative forcing.

Our analyses suggest that upland and wetland ecosystems of Alaska would act to warm the climate during the remainder of this century for four of the six climate projections we considered, and that it would act to cool the climate for one of the climate projections. For management regions within Alaska, our analyses indicate that for all climate projections, carbon dynamics of the Northwest Boreal LCC would act to warm the climate while carbon dynamics of the other LCCs would act to cool the climate. The statewide patterns largely depended on the magnitude of net CO_2 uptake in the simulations we conducted as the range of increase in CH_4 emissions was much narrower than that of net CO_2 uptake. It is important to recognize that if our assessment has a low bias in estimating CH_4 emissions to the atmosphere, then an unbiased estimate would result in a higher radiative forcing during the historical period. It is also important to recognize that the net CO_2 uptake we predict during the remainder of this century might not be sustained as suggested by the analyses of both Genet et al. (2017) and Lyu et al. (2018) because the sensitivity of NPP decreases for increasing levels of atmospheric CO_2. An analysis of permafrost carbon models out to the year 2300 generally indicated much larger net losses of carbon to the atmosphere from the northern permafrost region after the year 2100 because of both the decreasing sensitivity of NPP to increasing atmospheric CO_2 and substantially deeper thaw of permafrost (McGuire et al. 2018). It is also important for us to consider fluxes of CH_4 from rivers and lakes in estimating GHG radiative forcing. Although this assessment provided a first-order estimate of CH_4 from rivers and lakes in the historical period (Stackpoole et al. 2017), we did not include these estimates in our analysis of GHG radiative forcing. Also, we did not make projections of CH_4 emissions from aquatic inland ecosystems in this assessment. Models have recently been developed for simulating CH_4 emissions of arctic lakes (Tan et al. 2015), and these models may be useful for estimating regional CH_4 emissions of lakes in Alaska in future assessments to more fully inform policy decisions concerning the mitigation of greenhouse gas emissions in the United States.

Following IPCC guidance, countries may exclude areas from reporting national greenhouse gas inventories if they are designated "unmanaged," which is a proxy for greenhouse gas sources and sinks that are not significantly and directly affected by anthropogenic activities. This reflects the worldwide difficulty of making credible estimates of the anthropogenic influence in remote areas lacking infrastructure and common observation systems, and by implication, areas where disturbances such as timber harvesting are lacking and where fire suppression or controlling insect outbreaks is not practiced as intensely as in more populated regions. Nonetheless, the large size of Alaska, the high carbon densities in many ecosystems, and projections of potentially significant warming and natural disturbances mean that full accounting of U.S. carbon stocks and fluxes could be significantly compromised by excluding most of Alaska. Projections for the conterminous United States plus southeast Alaska indicate that the large U.S. carbon sink of more than 200 Tg C/yr will decrease significantly over the next 50 yr and potentially disappear altogether (Wear and Coulston 2015). What happens in the other regions of Alaska could enhance or potentially offset the carbon sink trends based only on the rest of the country.

Opportunities to manage the carbon cycle in Alaska are limited by remoteness and lack of infrastructure. Most forest management and harvesting occur in southeast Alaska, and like other areas with intensive timber harvesting and management, there may be some activities in this region that could increase carbon stocks (McKinley et al. 2011). For example, it may be possible to retain carbon stocks in the highest biomass forests by focusing future harvests on previously disturbed areas, or to increase the retention of harvested biomass in wood products by substituting wood for other construction materials that cause high emissions of fossil fuels during manufacture (Kurz et al. 2013). However, for most of Alaska not near population centers, it is impractical to expect substantive deployment of management actions that might limit impacts from wildfire and insect disturbances.

Recommendations for future assessments of carbon dynamics in Alaska ecosystems

It is important to recognize that there are many uncertainties in the results reported here. These include uncertainties associated with the methodology implemented and process-based models used in this assessment. At the top of the list of methodological uncertainties is the fact that the analyses of inland aquatic ecosystems were not integrated with those of upland and wetland ecosystems, which likely compromises the estimates of heterotrophic respiration because transfers of carbon from terrestrial to aquatic ecosystems are not taken into account. It is important to recognize that CH_4 emissions of lakes were not estimated for future climate projections, and whether or not future carbon dynamics in Alaska tend to warm or cool the climate may depend substantially on the magnitude of CH_4 emissions from inland aquatic ecosystems. The effects of insect disturbance were not considered in this study because of a lack of information on the effects of insects on carbon dynamics, the lack of a regional data set on historical insect disturbance, and the lack of a model capable of making estimates of future insect disturbance. Our analyses in this study also did not consider the effect of thermokarst disturbance associated with the thawing of ice-rich permafrost, which often results in the subsidence and the development of wetlands. Finally, with respect to methodological uncertainties, it is important for future assessments to extend the time period of analysis of projected carbon dynamics beyond 2100 given our inference that projected net CO_2 uptake during the remainder of this century may not be sustained. Our recommendation is to extend the time period to the year 2300 so that transitional carbon dynamics associated with permafrost thaw and photosynthetic saturation to elevated atmospheric CO_2 have enough time to become manifest (see McGuire et al. 2018 and Parazoo et al. 2018).

There are also substantial uncertainties associated with the process-based models used in this assessment. Although the process-based models we used were extensively evaluated in this assessment and in previous studies, they have substantial conceptual and parameterization uncertainties. These uncertainties have been discussed in Genet et al. (2017) and Lyu et al. (2018). Reduction in these uncertainties will require enhancements in observation systems, research on landscape dynamics, process-based research, and modeling research. Key enhancements in observation systems would include forest inventory measurements in interior Alaska, CO_2 concentration measurements in large lakes, measurements of CH_4 emissions from lakes and wetlands, and continued comprehensive airborne campaigns to estimate CO_2 and CH_4 exchange at large spatial scales and at seasonal, interannual, and longer timescales augmented with remote sensing analyses based on ground-based data of CO_2 and CH_4 exchange. Key enhancements in research on landscape dynamics include improved regional data sets on vegetation dynamics, lake dynamics, wetland distribution and dynamics, and insect and thermokarst disturbance. Key enhancements in process-based research would include improved understanding of the transfer of carbon between terrestrial and inland aquatic ecosystems, of CH_4 dynamics of inland aquatic ecosystems, and of controls over insect and thermokarst disturbance. Finally, key enhancements in modeling research would include the development of models that can treat terrestrial-aquatic carbon linkages as an integrated system, improved modeling of wetland and lake CO_2 and CH_4 dynamics, and the prognostic modeling of insect and thermokarst disturbance and their effects on carbon dynamics. Although there are substantial uncertainties in our analyses, the analyses themselves represent state-of-the-art science, and this assessment provides information for developing priorities to reduce uncertainties that should improve future assessments.

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Data Availability

Data available from: Scenario Network for Alaska Planning data portal: https://doi.org/10.5066/f7td9w8z. USGS Science Base: https://www.sciencebase.gov/catalog/item/59a40544e4b077f005673247