Chapter 9. Alaska Carbon Balance

By A. David McGuire,[1] Hélène Genet,[2] Yujie He,[3] Sarah Stackpoole,[4] David D'Amore,[5] T. Scott Rupp,[2] Bruce K. Wylie,[6] Xiaoping Zhou,[7] and Zhiliang Zhu[8]

9.1. Highlights

- Ecosystem carbon balance of the Alaska assessment domain (as outlined in chapter 1) was estimated for two time periods, a historical period (1950–2009) and a projection period (2010–2099) by synthesizing results for upland (chapter 6), wetland (chapter 7), and inland aquatic (chapter 8) ecosystems.
- The total area of Alaska considered in this assessment was 1,475,089 square kilometers (km^2) (97.9 percent of the State), which is composed of 84 percent uplands, 12 percent wetlands, and 4 percent inland waters.
- Between 1950 and 2009, the upland and wetland ecosystems of the State were estimated to have sequestered an average of 3.7 teragrams of carbon per year (TgC/yr) (–141.4 to 72.0 TgC/yr inter-annual variability), which was 1.5 percent of net primary productivity (NPP) in upland and wetland ecosystems. However, this sequestration is spatially variable with the Northwest Boreal Landscape Conservation Cooperative (LCC) North losing carbon because of fire disturbance and other regions gaining carbon.
- The combined carbon loss through various pathways of the inland aquatic ecosystems of Alaska was estimated to be 41.2 TgC/yr (5th and 95th percentiles of 30.4 TgC/yr and 59.7 TgC/yr), or about 17 percent of upland and wetland NPP.
- The greenhouse gas forcing potential of upland and wetland ecosystems of Alaska was estimated to be 17.3 teragrams of carbon dioxide equivalent per year during the historical period, and for the State as a whole was likely substantially larger because of methane (CH_4) emissions from lake ecosystems.
- During the projection period (2010–2099), carbon sequestration of upland and wetland ecosystems of Alaska were projected to increase substantially (18.2 to 34.4 TgC/yr) primarily because of an increase in NPP of 12 to 30 percent associated with responses to rising atmospheric carbon dioxide (CO_2), increased nitrogen cycling, and longer growing seasons. Although carbon emissions to the atmosphere from wildfire were projected to increase substantially for all of the projected climates, the increases in NPP would more than compensate for those losses.
- Upland and wetland ecosystems were projected to be sinks for greenhouse gases (GHGs) for all but one of the simulations during the projection period. However, as in the case of the analysis of the historical period, there was an uncertainty as to whether the State would be a net source for GHGs if emissions of CH_4 from lakes in Alaska were considered.

[1]U.S. Geological Survey, Fairbanks, Alaska.

[2]University of Alaska-Fairbanks, Fairbanks, Alaska.

[3]Purdue University, West Lafayette, Ind.

[4]U.S. Geological Survey, Denver, Colo.

[5]U.S. Department of Agriculture Forest Service, Juneau, Alaska.

[6]U.S. Geological Survey, Sioux Falls, S. Dak.

[7]U.S. Department of Agriculture Forest Service, Portland, Oreg.

[8]U.S. Geological Survey, Reston, Va.

9.2. 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 the overall ecosystem carbon balance of the State (Striegl and others, 2007; Zhuang and others, 2007; Wolken and others, 2011; Yuan and others, 2012). Thus, the response of carbon balance 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 carbon and greenhouse-gas inventory reports. Thus, the historical baseline carbon balance is poorly understood at a statewide level, and the potential for climate change to affect carbon dynamics in Alaska has not been formally assessed.

The main outcomes of this assessment for Alaska 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 greenhouse-gas (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. 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? Chapters 2 through 8 of this report addressed various aspects of these questions. This chapter focuses on synthesizing results across uplands, wetlands, and inland aquatic ecosystems to summarize information from this assessment at the statewide level on changes in carbon stocks, carbon fluxes, and greenhouse gas forcing for (1) historical/baseline (1950–2009) and (2) projection (2010–2099) periods.

9.3. Methods

9.3.1. Synthesis Estimates of Changes in Carbon Stocks

Changes in carbon stocks were estimated for upland and wetland ecosystems, but were not estimated for inland aquatic ecosystems because of a lack of data on carbon stocks in inland aquatic ecosystems. 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 (gC/m^2), at the end of December 1949 from the area-weighted mean at the end of December 2009 and then dividing by 60 years. The area-weighted means were obtained from the simulations conducted by the Dynamic Organic Soil version of the Terrestrial Ecosystem Model (DOS-TEM; Genet and others, 2013) for uplands (chapter 6) and wetlands (chapter 7). To convert to units of teragrams of carbon per year (TgC/yr), the mean change in carbon stocks for uplands and wetlands was multiplied by the area in square meters (m^2) occupied by uplands ($1.237774{\times}10^{12}$ m^2) and wetlands ($0.177069{\times}10^{12}$ 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 years.

9.3.2. Synthesis 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 ($gC/m^2/yr$) from 1950 through 2009. The area-weighted means were obtained from the simulations conducted by DOS-TEM for uplands (chapter 6) and wetlands (chapter 7). The mean flux was then multiplied by the respective area of uplands and wetlands (see above) to convert to units of TgC/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 and others, 2006) for upland and wetland ecosystems as follows:

$$NECB = NPP - HR - Fire - Harvest - BioCH_4 \quad (9.1)$$

for which the acronyms for the fluxes are defined as above.

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 chapter 8 in TgC/yr for the historical period.

9.3.3. Synthesis Estimates of Greenhouse Gas Forcing

We used the global warming potential (GWP) concept to estimate the greenhouse gas forcing potential across terrestrial upland and wetland ecosystems of Alaska. In our calculations of GWP, we assumed that CH_4 has 25 times the GWP of

CO_2 over a 100-year timeframe (Forster and others, 2007). GWP was reported in CO_2 equivalent: (1) C-CH_4 fluxes were converted to CH_4 equivalent by multiplying the fluxes by 16/12, the ratio of the molecular weight of CH_4 to the weight of carbon in CH_4, and the CH_4 equivalent fluxes were then converted to CO_2 equivalent multiplying them by 25, and (2) all C-CO_2 fluxes were converted to CO_2 equivalent by multiplying them by 44/12, the ratio of the molecular weight of CO_2 to the weight of carbon in CO_2. Positive GWP indicates net CO_2 emissions from the ecosystem to the atmosphere, and negative GWP indicates net removal of greenhouse gases by ecosystems.

9.4. Results and Discussion

9.4.1. Synthesis of Carbon Dynamics in the Historical Period (1950–2009)

Average soil carbon storage in Alaskan terrestrial ecosystems for the last decade of the historical period (2000–2009) was estimated to be 52.1 petagrams of carbon (PgC), with 47.1 PgC stored in upland ecosystems. Vegetation carbon storage in Alaskan terrestrial ecosystems over the same period was estimated to be 5.0 PgC with 4.3 PgC stored in upland ecosystems. The storage in upland ecosystems is greater because they occupy about 84 percent of the area (1.24 million square kilometers [km^2]) in Alaska compared with wetland coverage of 12 percent (0.18 million km^2); inland aquatic ecosystems occupy 4 percent (0.06 million km^2) of Alaska.

Between 1950 and 2009, upland and wetland terrestrial ecosystems of Alaska were estimated to have sequestered 3.7 TgC/yr (–141.4 to 72.0 TgC/yr inter-annual variability), which is 1.5 percent of annual NPP (table 9.1, fig. 9.1). This was largely because soil carbon sequestration (4.6 TgC/yr) more than offset losses of vegetation carbon (–0.9 TgC/yr). Upland ecosystems of Alaska were primarily responsible for the gain in soil carbon (5.3 TgC/yr) as wetland ecosystems were estimated to have lost soil carbon (–0.7 TgC/yr). Vegetation carbon was estimated to have decreased in upland ecosystems at –0.3 TgC/yr and in wetland ecosystems at –0.7 TgC/yr. The magnitude of NPP and HR in uplands was approximately six times greater than that in wetlands, and the loss of carbon in wildfire was three times greater in uplands than in wetlands. Modeled forest harvest was entirely concentrated in uplands, and modeled biogenic methane emissions were entirely concentrated in wetlands. 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 Landscape Conservation Cooperative (LCC) North (chapters 6 and 7). Although the Northwest Boreal LCC North lost soil carbon because of fire, upland ecosystems of other LCC regions gained soil carbon during the historical period.

Terrestrial upland and wetland ecosystems of Alaska were estimated to have been a carbon source of 17.3 teragrams of carbon dioxide equivalent per year ($TgCO_2$-eq/yr) with respect to greenhouse gas forcing of the climate system during the historical period as net CO_2 uptake from uplands (NPP − HR − Fire = −16.0 $TgCO_2$-eq/yr as a sink) was lower in magnitude than the global warming potential of wetlands (33.3 $TgCO_2$-eq/yr), which is dominated by biogenic methane emissions. It is important to note that harvested carbon was transferred from live vegetation to an inert carbon pool, and it did not contribute to our estimate of HR. If we had considered the decomposition of harvested carbon in our analysis, it would have resulted in terrestrial uplands and wetlands of Alaska being a larger net source of greenhouse gases between 1950 and 2009 than we have estimated.

Inland aquatic ecosystems were estimated to have lost 41.2 TgC/yr (5th and 95th percentiles of 30.4 TgC/yr and 59.7 TgC/yr) through export to the coast and CO_2 emissions from rivers and lakes, minus burial in lake sediments (table 9.2; fig. 9.1, chapter 8), which is about 17 percent of NPP in terrestrial ecosystems. This report does not include estimates of stock changes in aquatic ecosystems and, 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 Alaska coasts and carbon emissions across water surfaces is significant, and

Table 9.1. Sixty-year carbon balance of upland and wetland ecosystems in Alaska during the historical period (1950–2009).

[Soil carbon includes carbon in fibric, humic, and mineral soil horizons as well as carbon in coarse woody debris. Net ecosystem carbon balance is calculated as either change in vegetation carbon plus change in soil carbon or as net primary productivity minus heterotrophic respiration minus fire emissions minus biogenic methane emissions minus forest harvest. Positive values of net ecosystem carbon balance indicate increases in pools or fluxes of carbon into the ecosystem. Data may not add to totals or compute to net ecosystem carbon balance shown because of independent rounding. TgC/yr, teragram of carbon per year; $TgCO_2$-eq/yr, teragram of carbon dioxide equivalent per year]

Terrestrial component	Change in vegetation carbon	Change in soil carbon	Net primary productivity	Heterotrophic respiration	Fire emissions	Biogenic methane emissions	Forest harvest	Net ecosystem carbon balance	Global warming potential ($TgCO_2$-eq/yr)
	(TgC/yr)								
Upland	–0.3	5.3	212.0	175.0	29.0	0.0	2.9	5.0	–16.0
Wetland	–0.7	–0.7	37.3	27.3	10.4	0.9	0.0	–1.3	33.3
Total	**–0.9**	**4.6**	**249.2**	**202.3**	**39.4**	**0.9**	**2.9**	**3.7**	**17.3**

these results suggest that, when the processing and removal of carbon through inland waters is properly taken into account, the calculated capacity of soil and vegetation to store carbon and the heterotrophic respiration estimates for uplands and wetlands (table 9.1) may be reduced.

The methodology applied in this assessment does not allow us to combine the estimated carbon balance of upland and wetland ecosystems with the estimated carbon balance of inland aquatic ecosystems over the historical period. Thus, it is not clear whether Alaskan ecosystems have acted to sequester carbon in the historical period or whether they have lost carbon. The key methodological uncertainties concern both the heterotrophic respiration flux and the flux of carbon from terrestrial to inland aquatic ecosystems. The heterotrophic respiration estimate (205.2 TgC/yr, table 9.1) is likely an overestimate 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

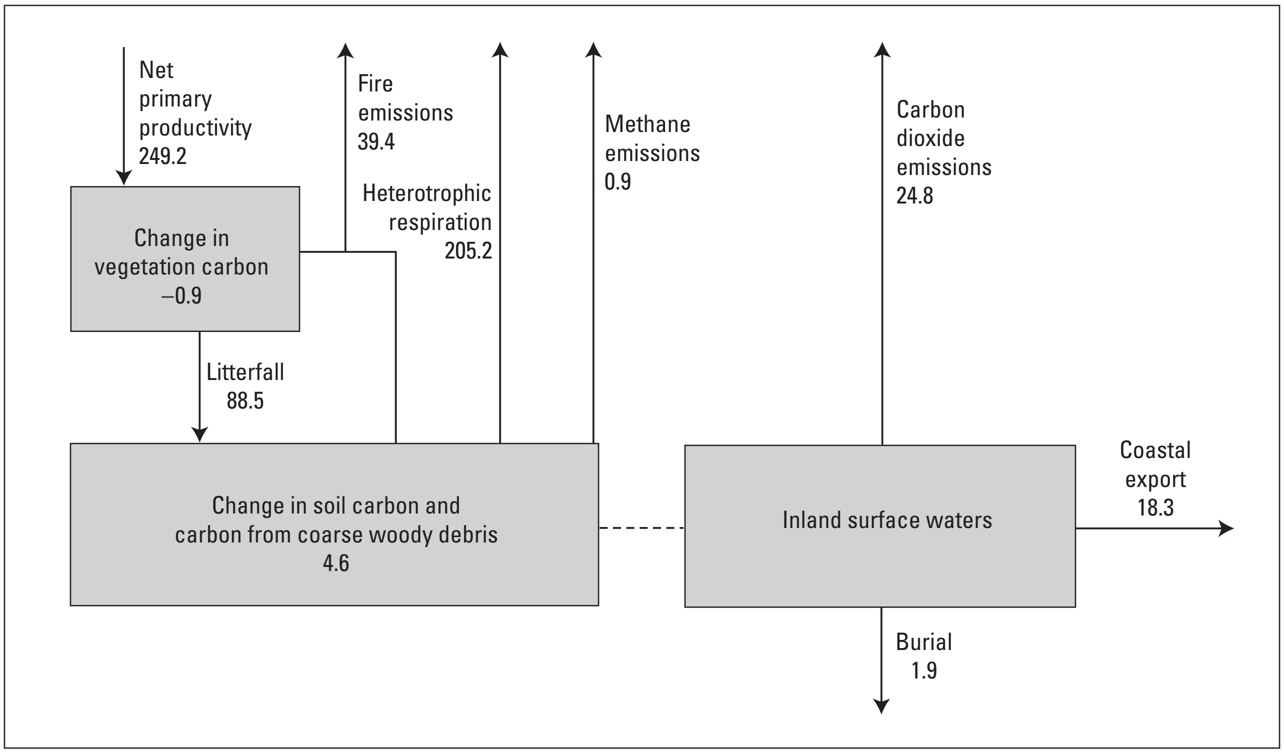

Figure 9.1. The carbon balance of the historical period (1950–2009) of this assessment estimated for the terrestrial (upland and wetland) component (left) and the inland aquatic component (right), in teragrams of carbon per year (TgC/yr). The arrows indicate the direction of carbon flows between the pools (including the atmosphere [not shown]) considered in this assessment. The litterfall flux of carbon from terrestrial vegetation to soil (88.5 TgC/yr) is provided in this figure to provide information relevant to the mass balance of terrestrial soil carbon. The linkage between fluxes of terrestrial vegetation and soil and that of the inland aquatic environment, as indicated by the dashed line, was not investigated in this assessment.

Table 9.2. Sixty-year carbon balance of inland aquatic ecosystems in Alaska during the historical period (1950–2009).

[Net ecosystem carbon balance for inland aquatic ecosystems is calculated as coastal carbon export from riverine systems plus carbon dioxide emissions from riverine systems plus carbon dioxide emissions from lacustrine systems plus methane emissions from lacustrine systems minus carbon burial in lacustrine systems. Because methane emissions from lacustrine systems were not estimated in this assessment, net ecosystem carbon balance was also not estimated. Net ecosystem carbon balance for aquatic systems can also be measured as change in carbon storage of inland aquatic ecosystems plus input of carbon into inland aquatic ecosystems from terrestrial (upland and wetland ecosystems), but neither of these was estimated in this assessment. TgC/yr, teragram of carbon per year; NE, not estimated]

Coastal carbon export from riverine systems (TgC/yr)	Carbon dioxide emissions from riverine systems (TgC/yr)	Carbon dioxide emissions from lacustrine systems (TgC/yr)	Methane emissions from lacustrine systems (TgC/yr)	Carbon burial in lacustrine systems (TgC/yr)	Net ecosystem carbon balance (TgC/yr)
18.3	16.6	8.2	NE	1.9	NE

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 uplands and wetlands (carbon sequestration of 3.7 TgC/yr, table 9.1). 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 State as a whole was likely a much stronger source for greenhouse gas forcing to the climate system than estimated from uplands and wetlands alone because of CH_4 emissions from lake ecosystems, which we did not estimate in this assessment.

The estimates of soil and vegetation carbon storage by DOS-TEM were validated with data independent from those used in model development (chapters 6 and 7). The evaluation of the soil carbon estimates of DOS-TEM generally indicated good agreement with other available products for Alaska (chapter 3). There were no available products of vegetation carbon storage at the statewide level with which to evaluate the vegetation carbon estimates of DOS-TEM.

The large-scale flux estimates of the historical period are difficult to evaluate with independent analyses, because these analyses are restricted in spatial and temporal scope. For example, the synthesis of eddy covariance data in Alaska by Ueyama and others (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 and others (2013) doesn't provide a quantitative means of evaluating the DOS-TEM simulations at the State scale and across the 60 years of the historical period. Our estimate of CH_4 emissions from wetlands for the historical period of 0.9 TgC/yr (1.2 teragrams of methane per year [$TgCH_4$/yr]) is substantially less than the estimate of 1.6 TgC/yr (2.1 $TgCH_4$/yr) for Alaska from May to September 2012 based on data from an aircraft sampling campaign (Chang and others, 2014). The difference in magnitude between the two estimates may, in part, be from CH_4 emissions of lakes, which we did not estimate in this assessment (table 9.2). Although the observational data on carbon dynamics in Alaska do not yet provide enough information for fully evaluating the exchange of greenhouse gases estimated by process-based models, the observational information is useful for some first-order evaluation of the magnitude and seasonality simulated by process-based models.

9.4.2. Assessment of Future Potential Carbon Dynamics (2010–2099)

Our assessment of future estimated carbon dynamics of Alaska (2010–2099) focused primarily on terrestrial upland and wetland ecosystems. The simulations indicated that carbon storage in terrestrial ecosystems would substantially increase across all six climate simulations—combinations of three climate scenarios (B1, A1B, and A2, in order of low to high projected CO_2 emissions) of the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (Nakićenović and Swart, 2000) used to force two general circulation models, version 3.1-T47 of the Canadian Centre for Climate Modelling and Analysis' Coupled Global Climate Model (CGCM3.1) and version 5 of the Max Planck Institute's European Centre Hamburg Model (ECHAM5). The range of carbon storage values, from 18.2 TgC/yr under scenario B1 with ECHAM5 to 34.4 TgC/yr under scenario A1B with CGCM3.1 (NECB in table 9.3), represents an approximate fivefold to ninefold increase over NECB for the historical period (3.7 TgC/yr, table 9.1). It should be noted that our simulations with DOS-TEM reported here did not model future forest harvest in southeast Alaska. The business-as-usual forest harvest we considered in chapter 5 for southeast Alaska would likely translate to an approximately 3-TgC/yr decrease in NECB (see chapter 6), and therefore would have little effect on the projected estimates of NECB we report here. The projected increase in carbon storage is primarily driven by increases in NPP of between 12 and 30 percent associated with increases in atmospheric CO_2 concentration, increases in nitrogen cycling, and longer growing seasons. Projected fire emissions across the climate simulations varied from a 36-percent decrease to a 212-percent increase. Projected HR across the climate simulations varied from an 18-percent decrease to a 13-percent increase primarily because increased fire in the Northwest Boreal LCC North would cause a substantial decrease in HR in that region associated with the substantial loss of soil carbon in fire. In other LCC regions, HR would increase in the future because of warmer soils, which would lead to higher rates of nitrogen cycling that increase NPP and lead to greater soil carbon stocks.

Our simulations indicated that terrestrial uplands and wetlands would act as sinks for greenhouse gases from 2010 through 2099 with GWP ranging from –24.5 to –91.6 $TgCO_2$-eq/yr, except for one simulation (11.6 $TgCO_2$-eq/yr, under scenario A1B with ECHAM5) for which biogenic CH_4 emissions and fire emissions were greater than for other simulations (table 9.3). Although we project that biogenic CH_4 emissions from wetlands will increase between 17 and 187 percent depending on the climate simulation, the increases do not offset the net increase in CO_2 uptake by upland and wetland ecosystems of Alaska for five of the six climate simulations in this assessment. This contrasts with our analysis for the historical period, which indicated that uplands and wetlands of Alaska were sources of greenhouse gas forcing. Because we did not assess the future dynamics of CH_4 emissions from lakes, we do not know if Alaska would be a net sink or source for greenhouse gases in the future.

Table 9.3. Projected carbon balance and global warming potential of terrestrial upland and wetland ecosystems in Alaska for the projection period (2010–2099).

[The six climate simulations are combinations of two general circulation models, version 3.1-T47 of the Coupled Global Climate Model (CGCM3.1) developed by the Canadian Centre for Climate Modelling and Analysis and version 5 of the European Centre Hamburg Model (ECHAM5) developed by the Max Planck Institute, and three climate scenarios of the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (Nakićenović and Swart, 2000), B1, A1B, and A2, in order of low to high projected CO_2 emissions. Soil carbon includes carbon in fibric, humic, and mineral soil horizons as well as carbon in coarse woody debris. Net ecosystem carbon balance is calculated as either change in vegetation carbon plus change in soil carbon or as net primary productivity minus heterotrophic respiration minus fire emissions minus biogenic methane emissions. Positive net ecosystem carbon balance indicates an increases in pools or fluxes of carbon into the ecosystem. Positive global warming potential indicates a net flux of greenhouse gas from the ecosystem to the atmosphere. Data may not compute to net ecosystem carbon balance shown because of independent rounding. TgC/yr, teragram of carbon per year; $TgCO_2$-eq/yr, teragram of carbon dioxide equivalent per year]

Climate scenario	Change in vegetation carbon (TgC/yr)	Change in soil carbon (TgC/yr)	Net primary productivity (TgC/yr)	Heterotrophic respiration (TgC/yr)	Fire emissions (TgC/yr)	Biogenic methane emissions ($TgCO_2$-eq/yr)	Net ecosystem carbon balance (TgC/yr)	Global warming potential ($TgCO_2$-eq/yr)
CGCM3.1								
A1B	8.8	25.6	292.6	232.0	25.1	36.1	34.4	–91.6
A2	10.2	21.9	306.6	168.7	103.4	64.4	32.2	–51.0
B1	6.2	20.5	278.2	219.9	30.4	37.1	26.8	–62.4
ECHAM5								
A1B	12.6	8.9	324.1	176.9	122.7	88.7	21.4	11.6
A2	12.5	11.7	323.3	190.5	106.4	54.1	24.3	–31.2
B1	9.8	8.5	282.3	222.4	40.3	43.3	18.2	–24.5

9.5. Conclusions

Our synthesis of carbon dynamics in Alaska indicates that between 1950 and 2009 the upland and wetland ecosystems of the State have sequestered 3.7 TgC/yr, which is almost 2 percent of upland and wetland NPP. However, this sequestration was spatially variable, with the Northwest Boreal LCC North losing carbon because of fire disturbance and other regions gaining carbon. We estimate that inland aquatic ecosystems of Alaska lost 41.2 TgC/yr, or about 17 percent of upland and wetland NPP, through various pathways. We estimate that the greenhouse gas forcing potential of upland and wetland ecosystems of Alaska was a source during the historical period, and we infer that the State as a whole was likely an even greater source for greenhouse gas forcing to the climate system because of CH_4 emissions from lake ecosystems, which we did not estimate in this assessment.

In contrast to the historical period, our synthesis of carbon dynamics in the projection period (2010–2099) indicates that carbon sequestration of upland and wetland ecosystems of Alaska would increase substantially (18.2 to 34.4 TgC/yr) primarily because of an increase in NPP of 12 to 30 percent associated with responses to rising atmospheric CO_2, increased nitrogen cycling, and longer growing seasons. Although carbon emissions to the atmosphere from wildfire were projected to increase substantially for all climate simulations, the increases in NPP would more than compensate for those losses. Our analysis indicates that upland and wetland ecosystems would be sinks for greenhouse gases for all scenarios during the projection period. Because we did not assess the future dynamics of CH_4 emissions from lakes, we do not know if Alaska would be a net sink or source for greenhouse gases in the future.

The results of our synthesis have implications for carbon management strategies that might be implemented as part of national policies aimed at controlling the rate and overall magnitude of climate change. These results suggest that Alaska could be a sink for greenhouse gases under some climate scenarios, but under others it could be a source, depending on the response of CH_4 emissions of lakes. However, it is important to recognize that CH_4 emissions from lakes have not been considered in this assessment, and it is likely that Alaska would be a source of greenhouse gases under all climate simulations if these emissions were considered in the assessment. Models have recently been developed for simulating CH_4 emissions of arctic lakes (Tan and others, 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.

It is important to recognize that there are many uncertainties in the results reported here. At the top of the list 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 losses of carbon to aquatic ecosystems are not taken into account. Also, CH_4 emissions of lakes were not quantified in either the historical or projection time periods, and whether or not Alaska is a sink or source of greenhouse gases depends substantially on the magnitude of CH_4 emissions from lakes. 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 dataset 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, the process-based models used in this study, although extensively evaluated in this assessment and in previous studies, also have substantial conceptual and parameterization uncertainties. These uncertainties have been discussed in chapters 6, 7, and 8. 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, and measurements of CH_4 emissions from lakes and wetlands. Key enhancements in research on landscape dynamics include improved regional datasets on vegetation dynamics, lake 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 priorities in reducing uncertainties that should improve future assessments.

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