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Sources and Sinks of Carbon in Boreal Ecosystems of Interior Alaska

A Review

Thomas A. Douglas, Miriam C. Jones, Christopher A. Hiemstra
and Jeffrey R. Arnold

July 2021

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Preface

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This paper was originally published on 12 December 2014 in *Elementa: Science of the Anthropocene*. Much of the information and ideas presented in this paper were borne from discussions with a wide variety of colleagues representing numerous disciplines and we are thankful that such a collaborative community is working on these topics. Many of the topics and content presented were strengthened by hearty discussions with Torre Jorgenson. An earlier version of this manuscript benefitted greatly from the detailed and thoughtful reviews of Teresa Hollingsworth and Jon O'Donnell. We would also like to thank the anonymous reviewers who provided detailed constructive suggestions on how to improve the manuscript. GIS content was provided by collaborators at the U.S. Army Alaska Directorate of Public Works and Colorado State University.

The Commander of ERDC was COL Teresa A. Schlosser and the Director was Dr. David W. Pittman.

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Sources and sinks of carbon in boreal ecosystems of interior Alaska: A review

Abstract

Boreal ecosystems store large quantities of carbon but are increasingly vulnerable to carbon loss due to disturbance and climate warming. The boreal region in Alaska and Canada, largely underlain by discontinuous permafrost, presents a challenging landscape for itemizing carbon sources and sinks in soil and vegetation. The roles of fire, forest succession, and the presence (or absence) of permafrost on carbon cycle, vegetation, and hydrologic processes have been the focus of multidisciplinary research in boreal ecosystems for the past 20 years. However, projections of a warming future climate, an increase in fire severity and extent, and the potential degradation of permafrost could lead to major landscape and carbon cycle changes over the next 20 to 50 years. To assist land managers in interior Alaska in adapting and managing for potential changes in the carbon cycle we developed this review paper by incorporating an overview of the climate, ecosystem processes, vegetation, and soil regimes. Our objective is to provide a synthesis of the most current carbon storage estimates and measurements to guide policy and land management decisions on how to best manage carbon sources and sinks. We surveyed estimates of aboveground and belowground carbon stocks for interior Alaska boreal ecosystems and summarized methane and carbon dioxide fluxes. These data have been converted into similar units to facilitate comparison across ecosystem compartments. We identify potential changes in the carbon cycle with climate change and human disturbance. A novel research question is how compounding disturbances affect carbon sources and sinks associated with boreal ecosystem processes. Finally, we provide recommendations to address the challenges facing land managers in efforts to manage carbon cycle processes. The results of this study can be used for carbon cycle management in other locations within the boreal biome which encompasses a broad distribution from 45° to 83° north.

1. Introduction

The boreal forest biome is the largest terrestrial biome on Earth, extending roughly from 45° to 83° N, and consisting primarily of coniferous forests with thick organic soils. Much of the boreal biome is underlain by permafrost. Permafrost, defined as any substrate remaining below 0°C for more than two consecutive years, can persist where mean annual air temperatures are as high as +2°C. This is due to localized differences in the soil thermal regime, which is influenced by topography, slope, aspect, hydrology, winter snowfall, ground ice content, soil texture, plant cover, and fire history (Osterkamp and Romanovsky, 1999; Hinzman et al., 2003a; Jorgenson and Osterkamp, 2005; Myers-Smith et al., 2008). Regional temperatures are not low enough to sustain permafrost everywhere (Schuur et al., 2008). Permafrost affects the vertical movement of water and nutrients through the soil column, so its presence can markedly affect surface soil and vegetation processes that are major aspects of the carbon cycle (Petrone et al., 2006; Walvoord and Striegl, 2007).

Climate warming is expected to have pronounced effects on high latitude ecosystems, especially in locations underlain by relatively warm, discontinuous permafrost such as interior Alaska (Arctic Climate Impact Assessment, 2005; White et al., 2007). Large areas of interior Alaska permafrost now show signs of

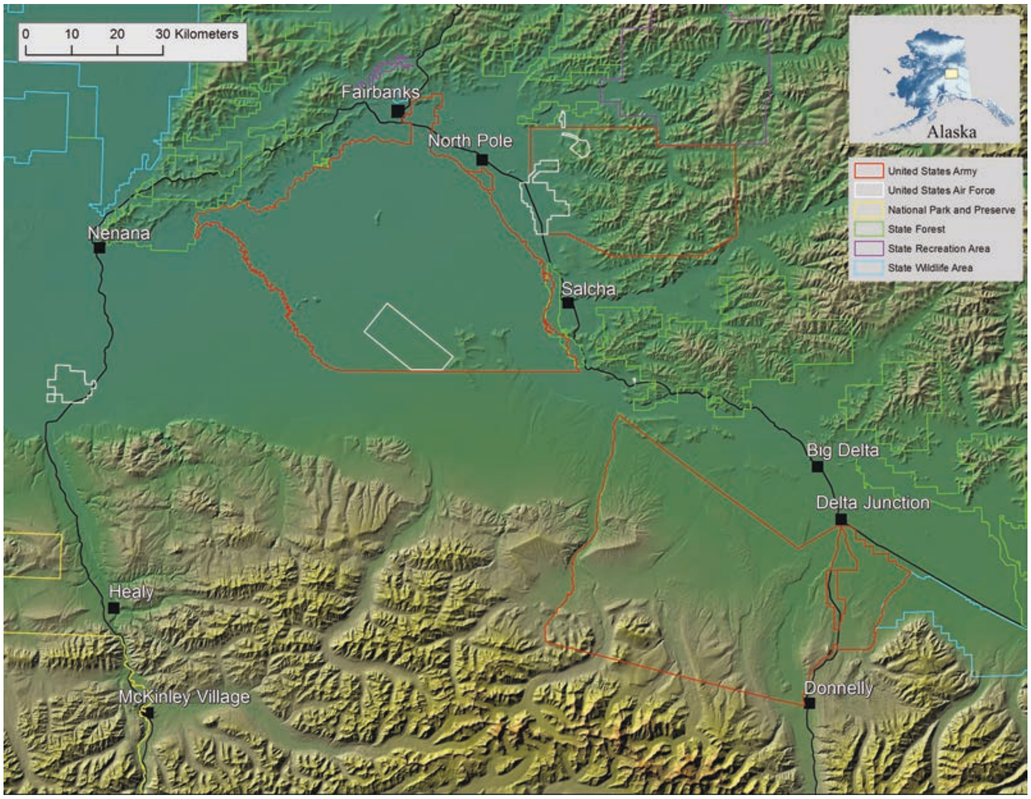

Figure 1

A map of our focus region in interior Alaska.

Boundaries of the major state and federal government landowners. The majority of the non-Federal and non-State of Alaska lands are owned privately or by Alaska Native Corporations.

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degradation (Racine and Walters, 1994; Jorgenson et al., 2001; Osterkamp, 2007; Osterkamp et al., 2009) and these are expected to continue to degrade with further climate warming (Marchenko et al., 2008). Changes in permafrost distribution have dramatically affected ecosystems across the boreal and arctic regions through widespread drying in some regions (Riordan et al., 2006; Roach et al., 2011) and wetland expansion in others (Racine and Walters, 1994; Osterkamp and Jorgenson, 2006).

Future climate scenarios project a roughly 5°C increase in mean annual air temperatures for the Alaskan interior over the next 80 years (Chapman and Walsh, 2007). This will be enough to initiate permafrost degradation in many areas (Osterkamp and Jorgenson, 2006; Marchenko et al., 2008), and is expected to lead to major changes in vegetation (Potter, 2004; Walker et al., 2006; Wolken et al., 2011), biological and physical processes in soils, and hydrology (Tarnocai and Campbell, 2002; Davidson and Janssens, 2006; Allison and Treseder, 2011; Johnson et al., 2011; Sierra et al., 2010; Douglas et al., 2013). Changes in permafrost extent and stability will alter carbon source–sink dynamics and provide a management challenge for future planning scenarios. There is great concern that permafrost thawing will yield increased carbon emissions from arctic and subarctic landscapes and provide a positive feedback to global climate warming (Frey and Smith, 2005; McGuire et al., 2009; Koven et al., 2011; Schaefer et al., 2011; Schuur and Abbott, 2011).

The goal of this review is to assist land managers in adapting and managing for potential changes in the interior Alaska carbon cycle by incorporating an overview of the climate, ecosystem processes, vegetation types, and soil regimes of the boreal biome in interior Alaska. Our area of interest is the northern portion of the Tanana River Valley spreading from west to east between the Alaska Range to the South and the hills north of Fairbanks (Figure 1; Van Cleve and Viereck, 1983). This area encompasses 15,000 square miles (3.8 million hectares), slightly larger than Maryland. The main federal government land managers include the Department of Defense (primarily the Army) and the National Park Service. State of Alaska lands include forest, recreation, and wildlife areas. The remaining lands are owned either privately or by Alaska Native Corporations. Though our main focus is the region of interior Alaska the studies and information presented in this paper are applicable to boreal regions in Canada and Alaska.

Our objective is to provide a synthesis of the most current carbon source and sink estimates and research results to guide policy and land management decisions on how to manage carbon stocks in interior Alaska, and potentially in other boreal landscapes. A number of thorough review articles exist on the carbon sequestration potential of forest soils (Goodale et al., 2002; Lal, 2005) and the vulnerability of soil organic carbon (McGuire et al., 2010; Grosse et al., 2011; Harden et al., 2012), permafrost carbon (Schuur et al., 2008; Schaefer et al., 2014), and the carbon cycle (McGuire et al., 2009) to boreal forest climate change and disturbance. Euskirchen et al. (2010) provide an overview of biogeochemical feedbacks with climate change in Alaska's boreal forests and Hobbie et al. (2002) focused on the relationship between nutrient availability and carbon dynamics. An excellent synthesis of the impacts of climate change on Alaskan forests was provided by Wolken et al. (2011) and terrestrial ecosystem feedbacks to the climate system are presented in Field et al. (2007). However, the aforementioned studies and review papers were not focused on supporting land management activities with respect to assessing and managing carbon sources and sinks.

To support our objective we: 1) synthesize results from numerous studies on the carbon cycle with a focus on research from the Alaskan boreal biome, 2) provide estimates of carbon sources in soil and vegetation in interior Alaska, 3) pinpoint potential sources and sinks for carbon on landscapes in interior Alaska, 4) identify expected changes in sources and sinks with climate change and human disturbance including how compounding disturbances can affect the boreal system, and 5) provide recommendations to address some of the impending challenges facing land managers in their carbon itemization efforts.

2. Background

A growing need exists for carbon source and sink inventories as the first step in identifying and implementing effective climate change mitigation strategies. Executive Order 13514 (Federal Leadership in Environmental, Energy, and Economic Performance) was released in October, 2009. One aspect of this Order requires U.S. Government agencies to account for greenhouse gas (GHG) emissions with the long-term goal of establishing emission-reduction targets. Actions taken by the federal government toward itemizing sources and sinks of GHG will likely dictate how state and local governments, non-profit, and for-profit entities follow. Most itemizations of GHG emissions focus on sources of CO_2 and CH_4 because they are anthropogenic greenhouse gases and major components of the global carbon cycle. CH_4 molecules are 21 times more effective at warming earth's greenhouse than CO_2 (Schlesinger, 1997). As a consequence, smaller CH_4 sources (or sinks) can play a comparatively large role in carbon itemization assessments.

Federal entities must address Executive Order 13514 across a wide variety of ecosystems, including the boreal biome which encompasses most of the land between 45° to 83° N and is the most broadly distributed terrestrial biome globally and in Alaska. This biome is characterized by dense forests with high carbon content soils and contains 49% of the global terrestrial forest carbon (Lal, 2005). In Alaska the region is characterized by extreme seasonality between winter and summer temperatures, dramatic seasonal variations in sunlight, a long-lasting snow cover, and a subsurface with heterogeneous bodies of discontinuous permafrost.

Atmospheric CO_2 and CH_4 can be derived from terrestrial ecosystem processes such as aerobic and anaerobic respiration and human activities, predominantly combustion and agriculture. Major CO_2 sinks include photosynthetic uptake, stabilization in soils, and the dissolution of CO_2 from soil and rock mineral weathering and calcium carbonate formation in the ocean. There is great uncertainty in identifying and quantifying the feedbacks between enhanced atmospheric CO_2 concentrations and whether the response of vegetation and soil microbes provide sources or sinks for this additional atmospheric carbon source (Hartley et al., 2012; Higgins and Harte, 2012; Van Huisstden and Dolman, 2012; Krankina et al., 2012).

Carbon dioxide (CO_2) and methane (CH_4) emissions into earth's atmosphere enhance the absorption of radiation emitted from earth's surface, resulting in warming. Anthropogenic activities contributing to elevated GHG concentrations in the atmosphere are dominated by fossil fuel burning, wildfires, and changing soil or vegetation regimes (Karl and Trenberth, 2003). This is compounded by the removal of GHG sinks when natural ecosystems undergo land use change and the attendant surface albedo and energy balance are altered (Pielke et al., 2007; Bonan, 2008).

3. The boreal biome of interior Alaska

3.1 *Climatic and physiographic setting*

The climate in interior Alaska is continental, with a mean annual air temperature of -3.3°C and typical mean monthly temperatures of 20.2°C in the summer (July) and -31.7°C in the winter (January) with extremes ranging from -51°C to 38°C (Jorgenson et al. 2001). The mean annual precipitation is 28 cm, with maximum annual snow fall of 1.7 m (Jorgenson et al., 2001). Approximately 40–45% of the annual precipitation arrives as snow (Liston and Hiemstra, 2011). In interior Alaska the permanent snow line is ~1,600 meters elevation in the Alaska Range to the south (Takeuchi, 2009). None of interior Alaska is above the permanent snow line.

The region is underlain by discontinuous permafrost that ranges from a few meters to over 50 m thick and is most commonly found on north facing slopes, in valley bottoms, and under poorly drained soils (Figure 2; Hopkins et al., 1955; Anderson, 1970; Hamilton et al., 1983; Jorgenson et al., 2001; Douglas et al., 2008). In locations with taliks (zones of unfrozen material created as permafrost thaws in areas below the seasonally thawed active layer) the spatial extent of permafrost bodies is extremely difficult to measure or predict. The horizontal and vertical heterogeneity of permafrost distribution in the area prevents the establishment of any simple estimation of permafrost extent.

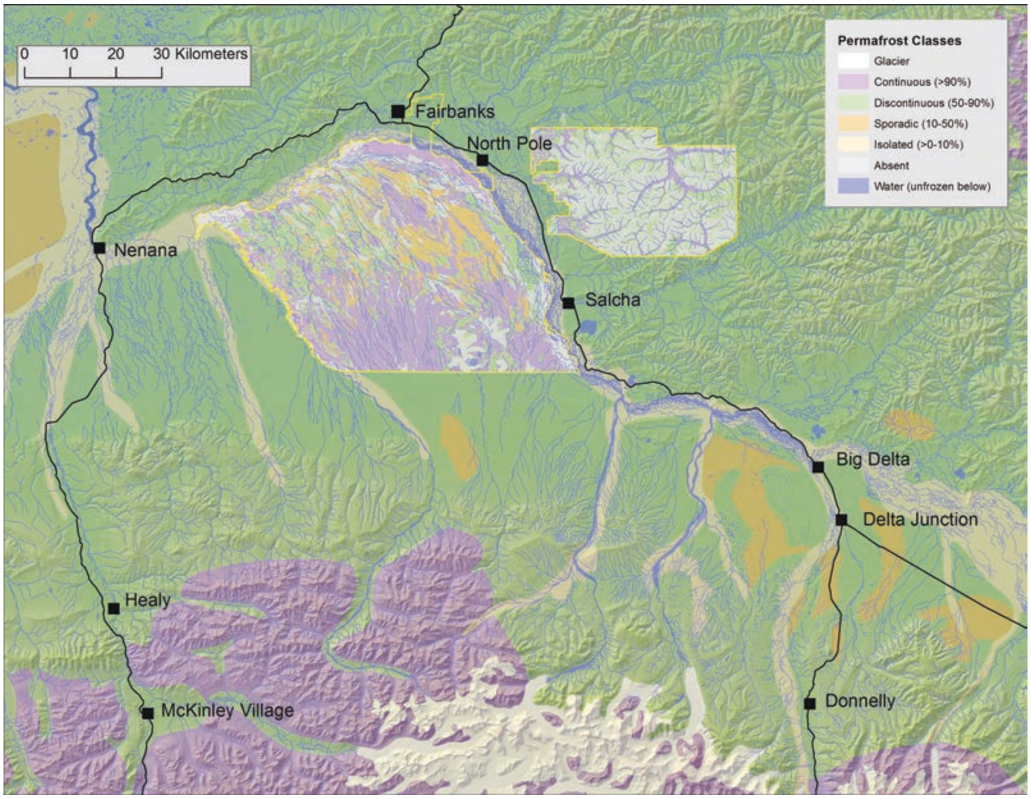

Figure 2

Extent and type of permafrost for the Tanana Flats and surrounding areas of interior Alaska.

Permafrost classes range from continuous to absent. Data sources for permafrost are varied with the majority from Jorgenson et al. (2008) and from the fine scale maps of the Department of Defense Tanana Flats and Yukon Training areas in Jorgenson et al. (1999). The spatial distribution of permafrost outside of the Tanana Flats and Yukon Training areas is not well mapped and is largely uncertain. Note that the Tanana Flats lowland directly south of Fairbanks and the uplands east of north Pole have been mapped at higher resolution than the rest of the mapped area (Jorgenson et al., 2008). As a consequence, for these areas a far richer dataset is presented.

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Permafrost acts as a confining bed in the subsurface that reduces soil water storage capacity and restricts groundwater flow (Hinzman et al., 1991; 1998; Kane et al., 1991; Woo, 2000). The presence of permafrost can greatly affect the stream discharge response to storm activity (Carey and Quinton, 2005), the geochemistry of stream flow (Petrone et al., 2006; Bagard et al., 2011), and seasonal fluxes of nutrients like carbon and nitrogen out of northern watersheds (Carey, 2003; O'Donnell and Jones, 2006; Frey et al., 2007; Frey and McClelland, 2009; Walvoord and Striegl, 2007; Cai et al., 2008a; 2008b; O'Donnell et al., 2012a; Douglas et al., 2013).

In interior Alaska, permafrost distribution correlates with physiography (Figure 3). Lowland landscapes are composed of a complex mosaic of forest, scrub, bog, fen, and open water bodies (Figure 4). They are underlain by sporadic bodies of ice-rich and ice-poor permafrost in gelisols predominately composed of organic material

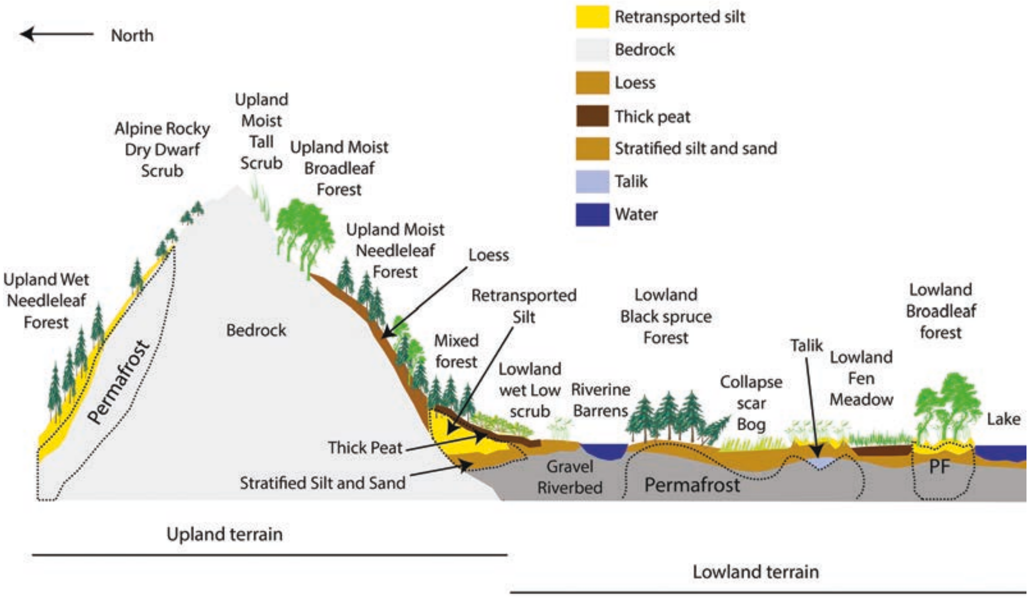

Figure 3

A cross section through upland and lowland terrains in interior Alaska.

A cross section illustrating the variety of land forms, hydrologic features, and vegetation in interior Alaska and their relationship to permafrost. Adapted from Jorgenson et al., 2010.

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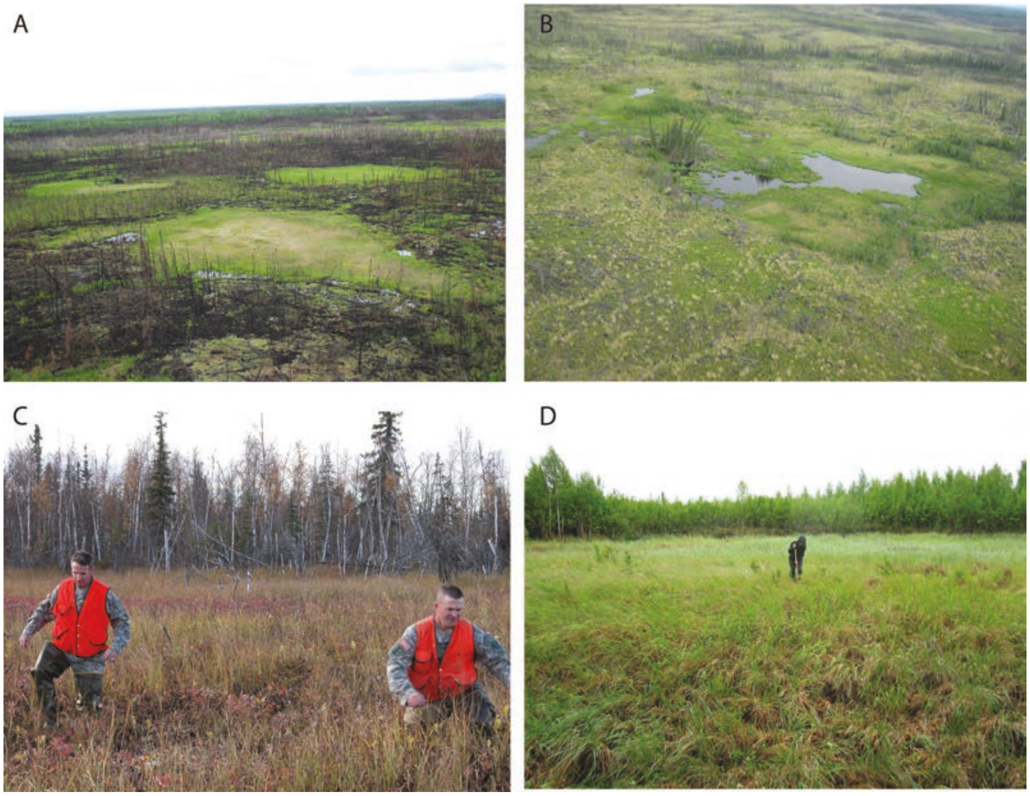

Figure 4

Photographs representing the vegetation typical of lowland ecosystems in interior Alaska.

A) An overview of an area that burned on the Tanana Flats in 2010. Green regions are locations where the vegetation is typical of a collapse-scar bog. The brown and black standing dead trees are characteristic of burned spruce and birch. B) A view showing the fen to forest transition in an unburned location in the fall. C) A close up of the fen from B. D) The vegetation typical of a bog. This area burned in 1988 and the dense forest in the background is typical of a birch forest.

Photos by Thomas A. Douglas

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(Pergelic Cryofibrists and Histic Pergelic Cryofibrists) or gravel, silt, and sand (Pergelic Cryochrepts; Brabets et al., 2000). The many open wetland corridors (floating vegetation mats and fens), thought to be permafrost free, are bordered by forests growing above permafrost or perched on top of well-drained gravel substrates. Lowlands comprise 42% of the boreal region in Alaska (574,000 square km), of which 13% is susceptible to collapse-scar bog formation (Jorgenson and Shur, 2007). These bogs form when permafrost acts as an aquiclude (a low flow zone in the subsurface around which flow is channeled) or an aquitard (a zone with no subsurface flow) a few meters below the surface. If a talik penetrates deep enough, the previously closed hydrological system can open up and increase contact with groundwater. In this case fens, wetlands with higher mineral and nutrient content, usually due to subsurface flow, can form. Racine and Walters (1994) suggest the large areas of fen wetlands are fed by groundwater discharge that moves northward from the Alaska Range to the south with permafrost acting as a confining layer channeling subsurface flow. Abundant slumping of trees indicate recent and past permafrost degradation along the upland margins of Tanana Flats.

Upland landscapes contain well-drained rocky or loess covered soils with permafrost occurring only on north-facing slopes and valley bottoms (Figure 5; Osterkamp et al., 2000; Jorgenson et al., 2001; Douglas et al., 2008). Soils include Alfic Cryochrepts on warmer, well drained south facing sites, and Histic Pergelic Cryochrepts at colder locations underlain by permafrost (Viereck et al., 1983). Upland permafrost tends to be more ice-poor and generally more thaw stable than lowland permafrost. Uplands have higher elevation gradients, drier soils, and more exposed bedrock than lowlands (Jorgenson et al., 2001). South facing and/or well-drained upland slopes tend to be free of permafrost (Osterkamp et al., 2000). The north slopes of the Alaska Range are composed of uplands containing rocky moraines with thick loess deposits.

3.2 Ecosystems of the boreal biome in interior Alaska

Slope, aspect, soil type and disturbance history play major roles in controlling vegetation composition in the Alaskan boreal forest just as they do in other places in the world. Vegetation in the boreal forest of interior Alaska (Chapin et al., 2006; Figure 6 and Tables 1, 2, and 3) is predominantly (40%) black spruce (*Picea mariana*) on permafrost, lowlands, and north-facing upland slopes, especially after low severity fires (Hollingsworth et. al 2006). Deciduous Alaska paper birch (*Betula neoalaskana*) and aspen (*Populus tremuloides*) with a matrix of either pure or mixed white spruce (*Picea glauca*) stands are common on uplands and south-facing slopes. *Sphagnum* spp. dominates the groundcover in poorly drained lowland black spruce forests, while feather mosses (*Pleurozium schreberi*, *Hylocomnium splendens*) are more common in drier sites. Mosses directly influence permafrost stability in the black spruce ecosystems by insulating the ground against summer heat (Jorgenson et al., 2010; O'Donnell et al., 2009; Turetsky et al., 2012). Moss cover, coupled with thicker organic

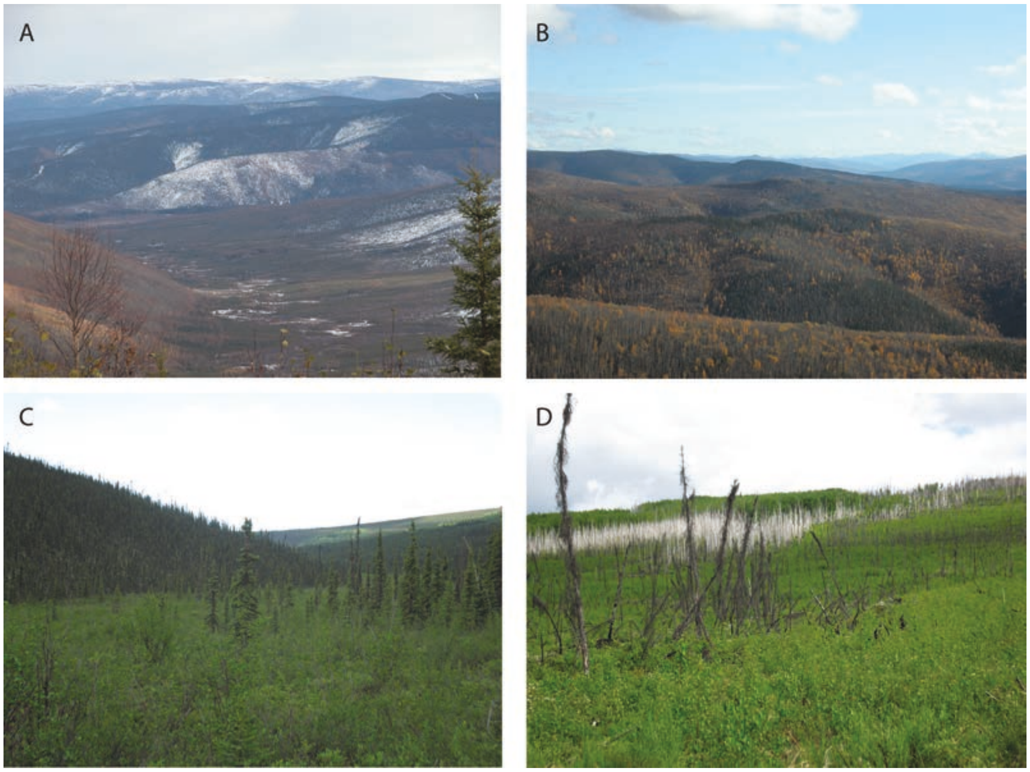

Figure 5

Photographs representing the vegetation typical of upland ecosystems in interior Alaska.

A) A winter time view of the Stuart Creek watershed showing the rolling hills and elevation gradients. B) A close up of the hills above Stuart Creek in late fall with mixed stands of birch-aspen forest and spruce (green). C) A valley bottom in the Caribou-Poker Creek Research Watersheds underlain by discontinuous permafrost with a spruce forest. D) A recent photo of a side hill in upland terrain in the Caribou-Poker Creek Research Watersheds that shows standing dead aspen trees (white colored crowns) from a 1999 fire. Standing dead spruce trees are visible in the foreground.

Photos by Thomas A. Douglas

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soils (0.5 to >3m) in black spruce stands are more protected against permafrost thaw than birch forests with no moss cover and little organic soil (Osterkamp et al., 2000). Mature black spruce stands typically have a well-developed carbon-rich surface organic layer dominated by a nearly continuous *Sphagnum* spp. ground cover in poorly drained locations and feathermoss and lichen on well- and moderately well drained sites (Trumbore and Harden, 1997; Hollingsworth et al., 2008).

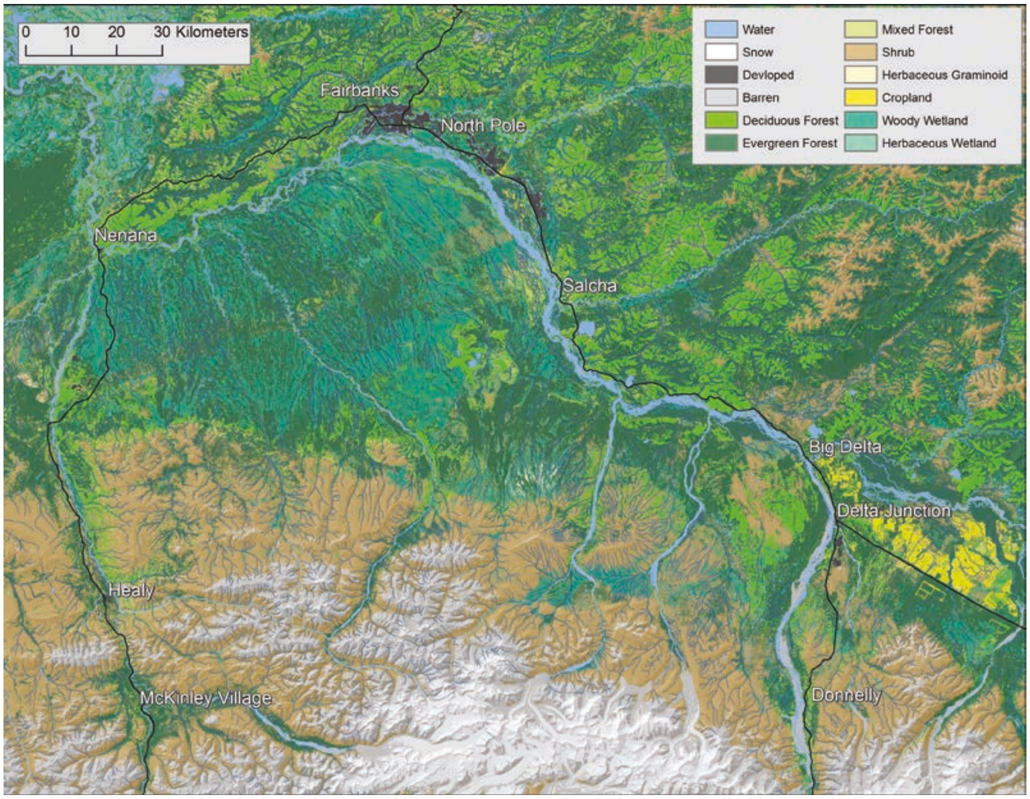

Figure 6

Predominant land cover classes for the Tanana Flats and surrounding areas of interior Alaska.

From the Alaska 2001 National Land Cover Database (Homer et al., 2007) including evergreen (34%) and deciduous (12%) forest, shrubland (24%), woody wetland (13%), and barren (7%). Percentages are calculated from Department of Defense owned lands within the visible domain.

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Table 1. Land cover types and their areal extent and percent coverage for the interior Alaska domain for three major U.S. Army training ranges (Tanana Flats, Donnelly, and Yukon), and for the U.S. Army Corps of Engineers Chena Lakes project

Physiographically, the Tanana Flats, Donnelly, and Yukon training lands are characterized as lowlands, uplands, and a mosaic of lowland and wetland terrains, respectively.

Cover type	Domain		Tanana Flats			Yukon			Donnelly			Chena Lakes		
	(ha)	%	cells	(ha)	%	cells	(ha)	%	cells	(ha)	%	cells	(ha)	%
Water	84,025	1.9	44,412	3,997	1.5	1195	108	0.1	69,620	6,266	2.4	104	9	1.0
Snow	120,336	2.7	0	0	0.0	0	0	0.0	18	2	0.0	0	0	0.0
Developed	27,060	0.6	18,507	1,666	0.6	2188	197	0.2	12,353	1,112	0.4	1,055	95	10.2
Barren	353,376	7.9	12,482	1,123	0.4	569	51	0.1	125,332	11,280	4.4	513	46	5.0
Deciduous Forest	540,606	12.1	289,282	26,035	9.6	419,301	37,737	36.1	292,485	26,324	10.2	661	59	6.4
Evergreen Forest	1,512,461	33.9	1,049,481	94,453	35.0	522,414	47,017	4500	733,346	66,001	25.5	450	41	4.4
Mixed Forest	156,588	3.5	96,214	8659	3.2	84,979	7,648	7.3	45,982	4,138	1.6	73	7	0.7
Shrub	1,080,602	24.2	94,298	8487	3.1	53,284	4,796	4.6	1,202,934	108,264	41.9	418	38	4.0
Herbaceous Graminoid	7,777	0.2	2,633	237	0.1	45	4	0.0	2,926	263	0.1	14	1	0.1
Cropland	22,694	0.5	1,334	120	0.0	71	6	0.0	1,424	128	0.1	3,436	309	33.2
Woody Wetland	517,018	11.6	1,366,955	123,026	45.5	76,732	6,906	6.6	383,837	34,545	13.4	3,443	310	33.3
Herbaceous Wetland	38,229	0.9	27,301	2457	0.9	105	9	0.0	1,039	94	0.0	169	15	1.6

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Alaska paper birch (*Betula neoalaskana*) and aspen (*Populus tremuloides*) are canopy dominants on well-drained, often permafrost-free mineral soils common in uplands, particularly on south facing slopes. White spruce ecosystems with moderately thick (20 cm) organic soil layers can also be found in uplands and in lowlands and north-facing upland slopes and are often underlain by permafrost. Typical understory vegetation includes high bush cranberry (*Viburnum edule*), dwarf dogwood (*Cornus canadensis*), willows (*Salix* spp.), lingonberry (*Vaccinium vitis-idaea*), bear berry (*Arctostaphylos uva-ursi*), and prickly wild rose (*Rosa acicularis*). Mixed forests typically have a less well-developed organic soil layer and only contain permafrost on north-facing slopes.

The ~8,000 km^2 Tanana Flats Lowland is an alluvial fan built from silt and gravel extending northward from the northern slopes of the Alaska Range (Cleve et al., 1993; Walters et al., 1998;). It forms a complex matrix of land cover types due to variability in the mineral substrate (silts to gravels), the local hydrology, and the presence of discontinuous permafrost. The patchy forest developed on the lowlands reflects differences in stand age related to time since last fire, the permafrost regime, and local flooding frequency. Collapse-scar bogs are common in the lowland black spruce forests and are dramatic features easily discerned with aerial photography. Deciduous forest stands generally have greater seasonally thawed active layer depths due to an absence of a moss groundcover that renders these locations more vulnerable to summer seasonal thaw. The ice contents of the birch forest vary widely and can reach greater than 50% while ice contents are closer to 20% in the black spruce stands (Osterkamp et al., 2000). Groundwater upwelling, ultimately sourced from the Alaska Range to the south, results in a matrix of nutrient-rich fens where permafrost is absent (Jorgenson et al., 1999). The fens are dominated by sedges and brown mosses (Table 2).

Permafrost depths have been documented up to 47 m thick within the Tanana River floodplain (Chacho et al., 1995), but they generally range from 0.5 to 12 m (Racine and Walters, 1994). A study undertaken in the late 1990s presented information on the extent of permafrost underlying the 263,759 hectares of U.S. Army Fort Wainwright training lands on Tanana Flats south of Fairbanks and between Nenana and Salcha (Figures 1, 2, and 4; Osterkamp et al., 2000). They reported 17% of the Tanana Flats training area lands were unfrozen, 48% had stable permafrost, 31% was partially degraded, and 4% was totally degraded.

3.3 *Disturbance and succession in the boreal biome*

3.3.1 Interior Alaska fire dynamics

Fire is the greatest ecologically important disturbance in the boreal biome (Viereck, 1973a; Zoltai et al., 1998; Kasischke et al., 2000a; Wurz et al., 2006; Barrett et al., 2011) affecting stand structure and species composition through patterns of mortality and regeneration (Johnstone and Chapin, 2006). Fire exerts significant influence on species composition and carbon cycling (Bond-Lamberty et al., 2007; Turetsky et al., 2011; Bernhardt et al., 2011; Table 4). The degree to which fire influences long-term boreal biome dynamics depends on fire severity, return interval, and burn depth (Viereck, 1973b; Johnstone et al., 2010; Beck et al., 2011). Recent study results suggest fires are growing larger, more intense, and more frequent in interior Alaska as a result of climate warming (Kasischke and Turetsky, 2006; Kasischke et al., 2010). Together, these factors have the potential to alter the long-term trajectory of forest regeneration (Johnstone and Chapin, 2006). The last decade experienced double the number of fires of any decade within the previous 40 years (Kasischke

Table 2. Lowland ecosystem types with their characteristic vegetation, permafrost regime, total area, and areal change information.

Ecosystem Type	Characteristic vegetation	Permafrost regime	Percent Total Area (1995)	Percent Area Change (1949–1995)[1]
Lowland black spruce forest	*Picea mariana, Ledum groenlandicum, Vaccinium uligunosum, V. vitis-idaea, Hylacomnium splendens, Pleurozium schreberi, Sphagnum fuscum*	Continuous/discontinuous	24	13
Lowland mixed forest	*Betula papyrifera, P. glauca, P. mariana, Rosa acuclaris, Calamagrostis Canadensis, Equisetum arvense*	Discontinuous	5	–3
Lowland birch forest	*Betula papyrifera, Rosa acicularis, Equisteum, arvense*	Discontinuous	15	–8
Lowland low scrub	*Betula nana, L. groenlandicum, V. uliginosum, V. vitis-idaea, Calamagrostis canadensis, Chamaedaphne calyculata, Sphagnum*		9	–11
Lowland Fen meadow	*(1) Calla palustris, Carex rostrata; (2) Equisetum fluviatile, Menyanthes trifoliata,Myrica gale, Chamaedaphne calyculata, Potentilla palustris, Typha latifolia, Cicuta mackenzieana, Galium trifidum; (3) Salix candida, Myrica gale*	Absent	40	8
Lowland Bog meadow (collapse scar)	*Sphagnum spp., Carex aquatilis, Eriophorum russeolum, E. angustifolium, Vaccinium oxycoccus*	At depth	7	–1
Lakes or Ponds		Absent or at depth	1	<1
Total degraded area			47	7

[1] Adapted from Jorgenson et al., 2001

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et al., 2010), a trend expected to continue as a result of potentially warmer and longer growing seasons (Duffy et al., 2005; Chapin et al., 2008; Balshi et al., 2009).

Fire is a natural part of boreal forest ecosystem dynamics and can regenerate food sources for large mammals such as moose and decrease insect outbreaks. Historically, most fires were caused by lightning strikes. Today, humans cause most fires but lightning-caused fires consume a greater areal extent. Based on our analysis of lightning strike density information provided by the Alaska Fire Service (Figure 7), we determined that 40% of the number of fires since 1947 were caused by lightning which has an uneven distribution across the landscape. Human activities, including accidents and prescribed burns, caused 47% of the fires, and the remaining 13% are attributed to a variety of other causes. Lightning strikes caused 57% of the area burned since 1947, while 26% were human caused, and 17% were attributed to other causes.

Over the period from 1947 to 2011, larger fires have occurred predominantly on lowlands, and the period from 2001 to 2011 experienced the largest area burned of any decade (Wendler et al., 2011), which also experienced an overall decrease in the number of fires per year compared to the 1970s and 1990s. These larger, more severe fires are generally associated with greater burn depths, higher carbon emissions, greater destruction of surface soils, enhanced permafrost degradation, and initiation of deciduous forests where the surface organic material burned down to mineral soils (O'Neill et al., 2002; 2003; Zhuang et al., 2003). These processes stimulate the decomposition of carbon that was previously locked frozen in permafrost and this leads to additional CO_2 emissions (Goulden et al., 1998).

In interior Alaska the number of lightning derived fires has increased over time (Kasischke and Turetsky, 2006; Turetsky et al., 2011) and lightning strikes are more prevalent in upland terrain versus lowland terrain (Figure 7). As would be expected, lightning strikes predominantly occur in the summer months with June and July accounting for most of the lightning in a given year (Wendler et al., 2011).

Fire has a large direct and immediate impact on carbon cycling as the combustion process causes the release of trace gases such as CO_2, CH_4, and CO and generates black carbon (Harden et al., 2000). In addition

Table 3. Upland ecosystem types with their characteristic vegetation and permafrost regime

Ecosystem type	Characteristic vegetation	Permafrost regime
Mixed forest	*Betula papyrifera, Picea glauca, Populus tremuloides, Alnus crispa, Rosa acicularis, Hylacomnium splendens,Pleurozium schreberi*	Minor to absent discontinuous
Birch-aspen forest	*Betula papyrifera, Populus tremuloides, Shepherdia Canadensis, Cornus Canadensis, Calamagrostis Canadensis, Pleurozium schreberi, Hylacomnium splendens*	Minor to absent discontinuous
White spruce forest	*Picea glauca, Ledum groenlandicum, Pleurozium schreberi*	Minor to absent discontinuous
Black spruce forest	*Picea mariana, Ledum groenlandicum, Vaccinium uligunosum, V. vitis-idaea, Empetrum nigrum Hylacomnium splendens, Pleurozium schreberi, Sphagnum fuscum*	Continuous/discontinuous

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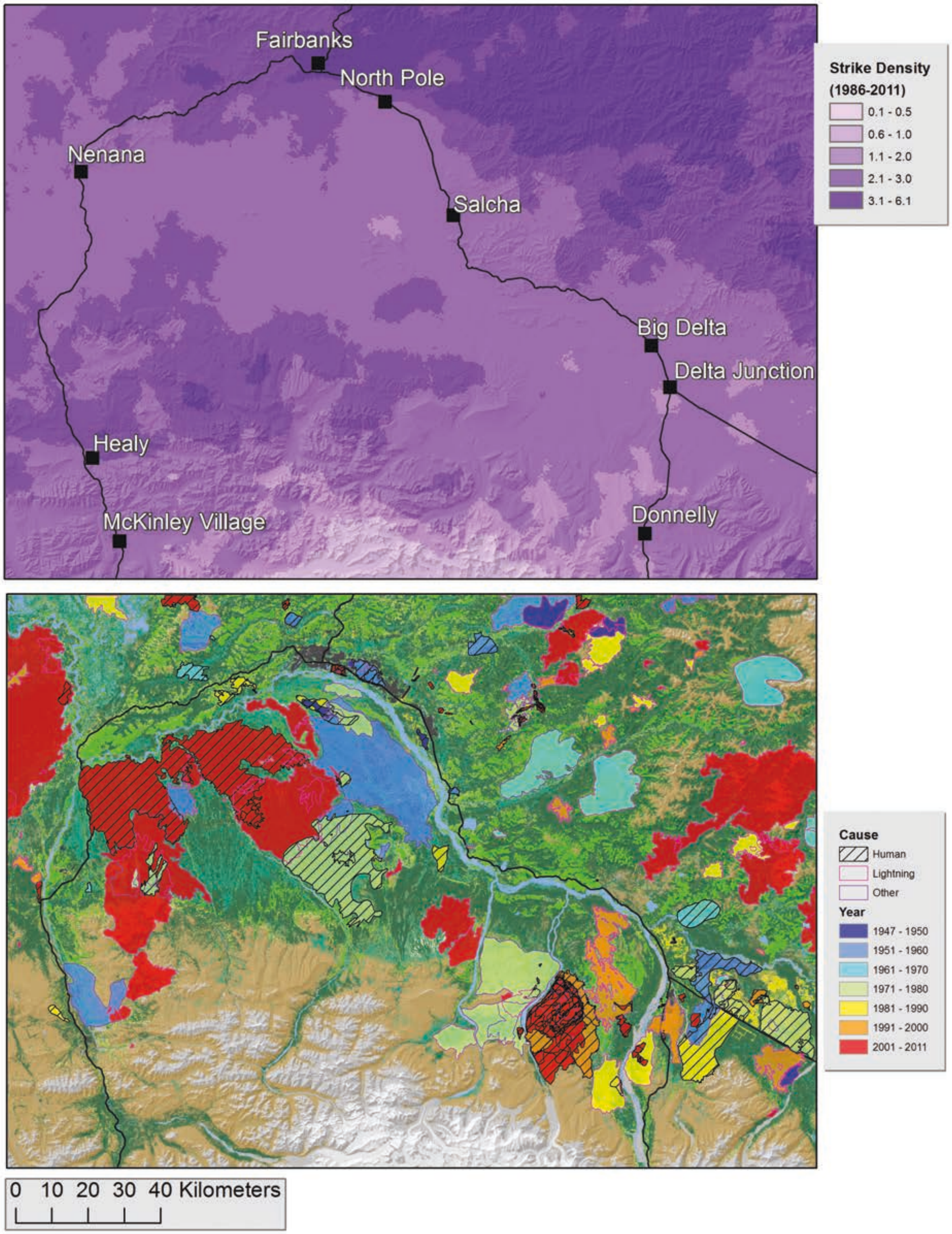

Figure 7

Lightning strike density and historical fire area information.

Top: lightning strike density (strikes per square km) occurring within a 5 km search radius from the center of each 500 m cell for the Tanana Flats and surrounding areas of interior Alaska. Data from the Alaska Fire Service (1986–2011; http://fire.ak.blm.gov/afs). Bottom: historical fire area data for interior Alaska from the Alaska Fire Service from 1947–2011 distinguished by the cause of each fire.

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Table 4. Soil carbon stocks for burned and unburned interior Alaska black spruce forest and peatland sites

The horizon thickness indicates the amount of carbon for the total measured depths.

Land cover	Unburned		Burned		Percent difference	Reference[1]
	Horizon thickness (cm)	C stock (g/m^2)	Horizon thickness (cm)	C stock (g/m^2)		
Black spruce	21	5,936	14	4,860	18.13	A
Black spruce	18	10,470	2	1,250	88.06	B
Peatland	21	41,648	21	11,238	73.02	A

[1] References:

A) O'Donnell et al., 2009

B) Iwata et al., 2011

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to the direct influences on carbon fluxes through biomass combustion, fires also influence successional patterns, which can have long-term consequences on carbon cycling (Shenoy et al., 2011) and permafrost stability (O'Donnell et al., 2012b). Historically, black spruce forests are burned through stand-replacing fires every 70–130 years with an average return interval for the overall boreal forest of about 29–300 years (Yarie, 1981; Dyrness et al., 1986; Kasischke et al., 2000b). Fire frequency and severity depend largely on the climate (i.e., meteorology) and on human activities such as suppression and ignition (Burn, 1998). Recent increases in burn severity have led to changes in successional trajectories that break the legacy of black spruce regeneration and this has led to a shift toward deciduous forest (Johnstone et al., 2010). These ecological shifts are facilitated by the combustion of the moss understory and organic soil layer that increases the mineral soil seedbeds that favor deciduous recruitment (Chapin et al., 2000; Johnstone and Kasischke, 2005; Kasischke and Johnstone, 2005; Johnstone and Chapin, 2006). Furthermore, unlike moderately-burned stands, where the organic soil remains and spruce trees have higher recruitment success, severely burned stands favor faster-growing deciduous tree species which outcompete spruce trees because their taproots, absent in spruce, help buffer against moisture stress.

Black spruce ecosystems are often underlain by permafrost that is thermally protected by the moss groundcover, particularly where hummock-forming *Sphagnum* mosses are present (Turetsky et al., 2010, 2011; Nossov et al., 2013). The thick organic layer in permafrost-impacted environments actively protects permafrost from thawing as part of the "ecosystem-protected permafrost" identified by Shur and Jorgenson (2007). The type of moss groundcover exerts an important control on the soil thermal regime since mosses with higher moisture content, such as *Sphagnum* mosses, protect the soil from warm summer temperatures better than feather mosses, which have a higher thermal conductivity (Yoshikawa and Hinzman, 2003). Since feather mosses are more likely to burn during fires, their presence or absence has a greater thermal impact on the thermal regime post fire. The depth of the active layer is largely dependent on the thermal conductivity of the soil, which is a function of density, moisture content, and thermal phase.

In a study of post-fire soil climate dynamics near Delta Junction, Alaska, Harden et al. (2006) found that the coldest, wettest soils were accompanied by the thickest organic mats. They also report that with every centimeter of organic mat thickness the temperature at 5 cm depth was 0.5°C cooler during the summer months. Model studies suggest that if an organic layer can remain >7–12 cm thick following wildfire, the impact of the fire on permafrost stability will be minimal (Yoshikawa and Hinzman, 2003). In fact, the largest driver of active layer thickness is the thermal conductivity of the organic layer, and as long as the organic thickness is not significantly altered, even with a decrease in surface albedo from the fire, the active layer is not significantly impacted. The importance of the organic layer and surface vegetation was also demonstrated by a study in which bulldozing of vegetation for fire lines showed more impact on active layer thickness than the severely burned black spruce during the 1971 Wickersham Dome fire. In this study the active layer was 161% deeper in the burned compared to the unburned forest (Viereck, 1982).

Fire chronosequence studies have shown that carbon fluxes are most dynamic in the first 20 years since fire with forests changing from a carbon source to a sink within roughly 10 years (e.g., Litvak et al., 2003; Welp et al., 2006; Randerson et al., 2006; Liu and Randerson, 2008; Amiro et al., 2010; Goulden et al., 2011). The largest control on the carbon cycle exerted by fires is the burn severity (Goulden et al., 2011; Iwata et al., 2011; Genet et al., 2013; Jafarov et al., 2013). An eddy covariance study of carbon exchange at a severely burned black spruce forest at the Poker Flat Research Range revealed the forest became a carbon sink within 5 years (Iwata et al., 2011). Despite the lower gross primary productivity, compared to other burned forest studies, respiration was also much lower because the fire consumed the organic soil layer.

In recent years the increased intensity of boreal fires has led to greater consumption of the protective moss layer resulting in enhanced permafrost thaw (Jorgenson et al., 2010). When this leads to ice-wedge degradation and thermokarst (subsidence of the ground surface following thaw of ice-rich permafrost) lakes are formed or relatively ice-rich permafrost thaws. These responses can cause collapse-scar bogs or other wetlands to form. Thawing permafrost compounds carbon cycle changes related to wildfire as ground subsidence changes forests to wetlands and lakes. An assessment of soil drainage in Alaska, as defined by water-holding capacity, hydraulic conductivity, and the position of the seasonal water table, showed a statistical correlation between poorly drained wet areas and historical burn (since 1950) which is likely related to the high C, and thus fuel load, of poorly drained soils (Harden et al., 2001). Punctuated drought or short-term seasonally dry soil conditions of these typically poorly drained soils could therefore promote burning and loss of belowground carbon.

Forest succession following fire, human disturbance, or floodplain development on the Tanana River floodplain initiates with willows (*Salix* spp.), followed by willow-alder (*Alnus tenuifolia*), then balsam poplar (*Populus balsamifera*) and white spruce (*Picea glauca*), and black spruce (*Picea mariana*) after the forest floor develops and organic matter begins to accumulate in the soil (Viereck et al., 1993; Hollingsworth et al., 2010; O'Donnell et al., 2012b). The emergence of black versus white spruce on floodplain soils may be due to differences in site drainage, which, in turn, is generally controlled by geomorphology (Mann et al., 1995; Hollingsworth et al., 2010). This succession process is associated with a steady accumulation of carbon in the vegetation and surface soils following flooding disturbance (Van Cleve et al., 1971; 1983; Nossov et al., 2011). Net primary productivity (NPP) decreases as the forest transitions from deciduous to needleleaf forest since nutrients become less available as organic matter builds up in the soil and a change to more recalcitrant species occurs (Berg, 2000). Development of black spruce/feathermoss systems constrains decomposition thermally, and this limits nutrient availability for net primary productivity (Lavoie et al., 2005; Wickland and Neff, 2008). Consequently, CO_2 uptake is low under slow-growing black spruce forests, but respiration (and thus CO_2 release) also slow as organic carbon accumulates in the soil. Minimal release of CH_4 occurs from these forests and in some cases they can act as a carbon sink (Euskirchen et al., 2010). Fire may alter this source-sink dynamic (Bond-Lamberty et al., 2007).

3.3.2 Nutrient dynamics

Changes in nutrient (e.g., N and P) availability can have large consequences on ecosystem structure and function, which impacts carbon cycling. Nutrient availability is low in boreal lowlands, such as bogs and black spruce forests, and species found in these systems are adapted to grow under reduced nutrient conditions. Fertilization has been shown to negatively impact evergreen shrubs growing in both bogs and black spruce forests in favor of grasses (Manninen et al., 2009). Along with understory vegetation, white spruce shows minimal growth response to nutrient addition (Nams et al., 1993). While increased spruce growth has been observed in Yukon Territory forest stands, cone and seed production of the spruce did not increase (Turkington et al., 1998). After disturbance, the amount of ammonia increased in the soil after fertilization and microbial C decreased, suggesting greater microbial C consumption following fertilization (Manninen et al., 2009). In a black spruce forest post-fire N addition resulted in a significant decline in soil C initially but total microbial biomass declined and lower respiration rates increased ecosystem C storage in black spruce forests experiencing frequent fires (Allison et al., 2010).

It is well known that bryophytes are negatively impacted by increased nutrients, especially *Sphagnum* mosses (Turkington et al., 1998; Güsewell et al., 2002; Juutinen et al., 2010; Turetsky et al., 2010). Bryophytes are more recalcitrant than the herbaceous understory vegetation that replaces them with increased nutrient fertilization. As a consequence, the amount of belowground carbon storage decreases with decreased bryophyte prevalence. A 9-year study of nutrient addition to the Mer Bleue peatland in eastern Canada showed a loss of bryophyte biomass over time and an associated decrease in overall ecosystem photosynthesis rates within five years. By the eighth year, net ecosystem exchange was nearly the same in the perturbed and control plots due to increased shrub growth where nutrients were added. However, ecosystem respiration rates increased 24–32%. This suggests high nitrogen deposition lessens the CO_2 sink strength of the bog (Juutinen et al., 2010). Ecosystems have also been found to recover quickly following nutrient drawdown (Limpens and Heijmans, 2008). Nutrient additions to certain ecosystems, such as deciduous forests, have the potential to increase net primary productivity and thus strengthen the CO_2 sink. In contrast, with moss-dominated bogs and black spruce understory, nutrient addition increases carbon cycling rates and has the potential to minimize the net carbon sink.

3.3.3 Human and biological disturbance

Any removal of the organic soil layer or moss ground cover will increase the ground heat flux, which promotes permafrost thaw. This includes road building, clearing fire lines, developing trails, airboat use in shallow water, and infrastructure development. On the Tanana lowlands, particularly in the wet fens and floating mats, disturbance by airboats has resulted in mortality of the plants on trails and ultimately more open water areas. The open water has a lower albedo than the highly reflective fen vegetation, which promotes further permafrost degradation. Evidence exists for an expansion of *Typha latifolia* and *Menyanthes trifoliata* along airboat trails (Racine and Walters, 1994) suggesting airboat traffic not only impacts plant growth but also changes the fen community. The presence of deeper water and more frequent disturbance decreases the ability of the fen to uptake carbon.

Extensive insect outbreaks have been associated with climate warming in Alaska. Most notable are the spruce bark beetle (*Ips typographus*) outbreaks that have reached epidemic levels and caused widespread spruce mortality on the Kenai Peninsula in south-central Alaska (Berg et al., 2006). There is currently little indication of spruce bark beetles in interior Alaska. Spruce budworm (*Choristoneura fumiferana*) outbreaks, which affected white spruce populations in interior Alaska in the late 1990s and mid-1980s, were attributed to climate warming and an increase in the rate of larval development (Han et al., 2000; Volney and Fleming, 2000). These insects caused a reduction in tree growth and density which likely reduced forest carbon uptake. Leaf miners (*Phyllocnistis populiella* Chambers) have extensively infested aspen stands in interior Alaska. They do not result in tree mortality but result in leaf abscission four weeks earlier in heavily mined leaves than healthy leaves, impacting rates of photosynthesis and carbon uptake (Wagner et al., 2008). As agents of disturbance, insects can decrease NPP and this can lead to a reduction in CO_2 uptake by forests (Fleming, 2000). A recent review by Hicke et al. (2012) covers the role of insect disturbance on the forest carbon cycle in a variety of locations including the boreal forest of Canada and the United States. They discuss the contradictory responses to disturbance whereby some forest stands exhibit increased primary productivity because surviving vegetation experiences increased growth while stands with repeated growth reductions experienced increased tree mortality and decreased productivity. They conclude that though biotic disturbances can have a major impact on forest C stocks and fluxes there are many uncertainties associated with quantifying the effects of disturbance on C budgets.

Alaska has relatively few invasive species, and most are limited to road margins and other clearings. One exception impacting the interior is *Melilotus alba,* an aggressive early successional monospecific colonizer, now found along several glacial river flood plains (Wurtz et al., 2010), including the Nenana River (Conn et al., 2011). *M. alba* has a significant advantage as an early colonizer because of its ability to fix large quantities of nitrogen, up to 100 kg/ha (Sparrow et al., 1993; 1995). At high densities the species can reduce seedling survival, cover, and density of native species (Conn et al., 2011). Another aggressive invasive in interior Alaska is the narrowleaf hawkweed (*Hieracium umbulatum*) which spreads aggressively on burned soil and along roadways (Cortés-Burns et al., 2007). If invasive species outcompete forest stands for water or nutrients and cause forest dieoffs and an increased presence of standing dead trees, fire prevalence and severity could increase, particularly in the immediate years following tree die-off.

Lodgepole pine (*Pinus contorta* var. *latifolia*), though not an invasive species, has been shown to have strong ecosystem effects where it has expanded into southern boreal forests, particularly as a dominant species following fire (Johnstone and Chapin, 2003) due to its high growth rates (Gutsell and Johnson, 2002). Interior Alaska has no species listed as threatened or endangered by the U.S. Fish and Wildlife Service. The American peregrine falcon (*Falco peregrinus anatum*), common in interior Alaska, was delisted in 1999.

3.4 Permafrost degradation in uplands and lowlands

Permafrost is common in lowland areas, covering roughly 80 percent of the lowland landscape (Figure 2). The presence (or absence) of permafrost is intricately linked to the local vegetation, soils composition, and surface hydrology. The extent of this permafrost is expected to decline in coming decades as a response to climate warming (Jorgenson et al., 2001). Thermokarst development increased 21% between 1949 and 1998 on Tanana Flats and the expected continuation of climate warming in the region could lead to permafrost elimination by 2100 (Jorgenson et al., 2001; Euskirchen et al., 2006; 2009; Lawrence et al., 2008). Due to its complex mosaic of soils, vegetation, permafrost extent and surface water bodies, the Tanana Flats lowland would be expected to respond dramatically and largely unpredictably to the degradation (and eventual total loss) of permafrost. Of particular concern is the potential loss or change of wetland habitats in the low gradient lowland locations if subsurface permafrost aquicludes or aquitards are lost.

Permafrost degradation leads to significant changes in peatland ecosystem carbon cycling (Camill, 1999; Camill et al., 2001; Turetsky et al., 2000; 2008; 2010; O'Donnell et al., 2012b; Wu, 2012). Ground subsidence following thaw typically results in surface inundation, an increase in hydrophilic taxa, and enhanced anaerobic decomposition, resulting in increased CH_4 flux and decreased CO_2 flux to the atmosphere (Bellisario et al., 1999; Turetsky et al., 2002; Wickland et al., 2006; Lee et al., 2012). In areas exposed to wind, ground subsidence can also foster increased snow depths and warmer winter soil temperatures (Zhang, 2005a). Following thermokarst initiation, the thermal capacity of the water then has the capability to continue to thaw the permafrost laterally (Camill, 2005; O'Donnell et al., 2012a). In locations where permafrost degradation leads to enhanced drainage and surface drying, greater oxidation reduces carbon accumulation rates (Robinson and Moore, 2000) and enhanced CO_2 release (Waelbroeck, 1993; Frolking et al., 2006).

In upland locations where permafrost is present, partial or initial degradation of permafrost can result in wetter soil conditions where inundation occurs or where drainage is limited by permafrost or low hydraulic soil conductivity. These wetter conditions may increase hydrophilic vegetation such as *Sphagnum* and sedges. However, as permafrost degradation continues, surface microtopographic changes could yield greater surface run-off and drying from higher topographic regions (Schuur et al., 2007). This drying kills mosses and tussocks (Schuur et al., 2007; Osterkamp et al., 2009) and enhances net CO_2 flux to the atmosphere.

3.5 Interior Alaska wetlands and hydrogeology

The boreal region contains a varied distribution of lakes that are stable, increasing, or decreasing. Lake stability is the result of heterogeneous permafrost, hydraulic gradients, and lake and catchment topography (Roach et al., 2011). Though they only cover ~2% of interior Alaska by area, lakes are an important component of the area's boreal ecosystems and their carbon cycle processes because of aquatic-terrestrial links between water bodies and the surrounding soil and vegetation. Nutrients, especially carbon and nitrogen, impact terrestrial ecosystems nearby, leading to enhanced lake productivity with increased run-off or permafrost thaw (Symstad et al., 2003; Ball et al., 2010).

The response of permafrost lakes to climate warming or other disturbance is not simple or uniform across the landscape (Roach et al., 2011; Rover et al., 2011). Time series remote sensing studies of the areal extent of thousands of lakes in arctic and sub-arctic Alaska have shown a general trend whereby lake area extents in the discontinuous permafrost zone tend to be decreasing, in some areas up to 31 percent of lake area coverage, while lake areal extents in the continuous permafrost zone are stable (Riordan et al., 2006). Lakes perched above continuous permafrost are believed to be more stable because they experience less vertical or horizontal drainage (Smith et al., 2005).

To determine the primary cause of lake drawdown in boreal Alaskan lakes, Roach et al. (2011) studied four lake regions and determined deeper lakes that formed from ice-rich thermokarst tended to be more persistent than shallow lakes (<1m) either absent of permafrost or perched on ice-poor permafrost. Terrestrialization was found to be the primary mechanism for lake drawdown (as opposed to subsurface talik drainage). In shallow, smaller volume basins, lake terrestrialization is thought to result from a combination of warmer water and greater proportional nutrient input that speeds vegetative productivity. Under a warmer climate this will increase transpiration rates (Roach et al., 2011), resulting in greater carbon uptake and vegetation growth (Keeling et al., 1996; Myneni et al., 1997).

In the Yukon Flats National Wildlife Refuge in Alaska, where stable isotope analyses revealed that ~95% of the studied lakes sourced water from precipitation, river water, and groundwater, lake lowering is predominantly the result of evaporative losses exceeding supply as a result of warming temperatures and no net change in precipitation (Anderson et al., 2013).

Another driver of shrinking lakes in discontinuous permafrost is the development of thermokarst which leads to talik development and subsurface drainage (Marsh and Neumann, 2001; Yoshikawa and Hinzman, 2003). Fire or human activities that remove surface vegetation can cause ice-rich permafrost to thaw differentially and amplify irregular surface topography (Hinzman et al., 2003b; Yoshikawa and Hinzman, 2003). Where disturbance leads to talik formation sub-surface lake drainage, surface drying, and the lateral movement of surface water can occur.

Fen, bog, and marsh systems, often linked hydrologically to lakes and ponds, also play major roles in nutrient cycling between aquatic and terrestrial ecosystems (Fan et al., 2013; Rober et al., 2014). Numerous studies at the Bonanza Creek Long-Term Ecological Research in interior Alaska have confirmed these results (e.g., Kane et al., 2010; Wyatt et al., 2010; Jones et al, 2013). In the discontinuous permafrost zone permafrost degradation may result in the partial or full disappearance of the permafrost aquiclude which can increase or decrease local hydraulic gradients depending on a variety of factors (Britton, 1957; Kane and Slaughter, 1973; Billings and Peterson, 1980; Woo, 1986; Jorgenson et al., 2001; Yoshikawa and Hinzman, 2003). Fen systems are particularly sensitive to water table fluctuations with studies showing rapid (i.e., on the order of days) increased CH_4 fluxes from fens when their water table elevations decrease (Roulet et al., 1992; Windsor et al., 1992). Flooded fens in interior Alaska were found to provide an increased CO_2 sink, whereas droughts reduced their carbon sink capacity and even turned them into small carbon sources (Chivers et al., 2009).

Watersheds underlain by permafrost exhibit an intense seasonality of flow paths, discharge, and streamwater biogeochemistry (O'Donnell and Jones, 2006; Petrone et al., 2006; Walvoord and Striegl, 2007; Barker et al., 2014). Recent studies in the Chena River watershed, a non-glaciated river draining the boundary between the Tanana Flats lowlands and nearby uplands, have shown a strong correlation between discharge and dissolved organic carbon (DOC) and total dissolved nitrogen (Cai et al., 2008a, 2008b; Douglas et al., 2013). Of particular note, nutrient exports are rapidly flushed from surface soils during large discharge periods such as snow melt runoff or major summer precipitation events. This is consistent with results from studies in other subarctic and arctic rivers (Striegl et al., 2005, Finlay et al., 2006; Raymond et al., 2007; Walvoord and Striegl, 2007; McNamara et al., 2008; Frey and McClelland, 2009; Guo et al., 2012). The DOC mobilized during high flow events is generally believed to be of modern age (Guo and Macdonald, 2006; Neff et al., 2006) and part of the DOC transported during spring melt may be labile (Holmes et al., 2008). Where changes in permafrost extent are sufficient to alter flowpaths, the carbon balance of subarctic watersheds could shift from a net sink to a net source (McGuire et al., 2009; Grosse et al., 2011). Since snow melt occurs during the major seasonal transition between winter and spring/summer any shift in the timing of snow melt would alter the timing of the major nutrient fluxes out of northern watersheds. However, the potential effects of this change in seasonality are unknown.

4. Climate change impacts in interior Alaska

4.1 Terrestrial changes as a response to a warming climate

High-latitude amplification of climate warming has caused Alaska's boreal biome to warm 1.3°C during the last 50 years (Shulski and Wendler, 2007), twice the rate of the global high latitude average (Arctic Climate Impact Assessment 2005, Hinzman et al., 2005; Solomon et al., 2007; Chapin et al., 2010). Future climate scenarios project a 3–7°C increase in mean annual air temperatures for the Alaskan interior over the next 90 years (Chapman and Walsh, 2007; Walsh et al., 2008). In addition to this increase in mean annual temperatures, the occurrence of extreme low temperatures (characterized by temperatures <-40°C) has decreased on average from 14 to 8 days annually (Wendler and Shulski, 2009). A non-statistically significant 11% decrease in annual precipitation has occurred over the last 90 years near Fairbanks (Wendler and Shulski, 2009) with the strongest decreases in precipitation occurring in spring followed by winter.

Shoulder-season and seasonal transitions are occurring. More of the annual precipitation is arriving as rain (Liston and Hiemstra, 2011), and snow blanketed the boreal landscape 17 days fewer in 2009 compared to 1979. Fall snow arrival happens two days per decade later. The spring snow cover from 1972–2008 (Brown et al. 2010) and 1979–2009 (Liston and Hiemstra, 2011) has been disappearing 5 days earlier per decade. This reduction in snow cover primarily comes at a critical time when insolation is high as summer approaches (Chapin et al., 2005; Derksen and Brown 2012), resulting in a dramatically higher energy influx and a longer growing/drought season. The lack of a substantial increase in precipitation will do little to offset higher summer evapotranspiration rates (Scenarios Network for Alaska Planning. 2010), which may result in drier soils, lower lake levels, and increased fire potential.

We present historical data and projected future air temperature and precipitation information during summer and winter in interior Alaska in Figures 8 to 15. Temperature outputs (Figures 8, 10, 12, and 14) are taken from the Scenarios Network for Alaska and Arctic Planning (SNAP; http://www.snap.uaf.edu) program's selected model results derived from climate model simulations from five climate models that perform well in Alaska, together with their multi-model average. These five models are: the Canadian Centre for Climate Modelling and Analysis General Circulation Model version 3.1, the Max Planck Institute European Centre Hamburg Model 5, the US National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory Coupled Climate Model 2.1, the United Kingdom Meteorological Office Coupled Model 3.0, and the Japan Center for Climate System Research Model for Interdisciplinary Research on Climate-medium resolution. The B1, A1B, and A2 scenarios (Intergovernmental Panel on Climate Change, 2000) represent, respectively, relatively lower, intermediate, and higher CO_2 emission futures (Solomon et al., 2007) created for the World Climate Research Program's Coupled Model Intercomparison Project, Phase 3 (CMIP3). Outputs from the five GCMs selected for SNAP and used here were statistically downscaled for the SNAP program from the GCM native scales to the sub-continental scales of Parameter-elevation Regressions on Independent Slopes Model (PRISM; http://prism.oregonstate.edu) data in Alaska (2km or 0.771km, depending on year) using a delta method with spline fitting on the anomalies in monthly temperature and precipitation as projected and compared to observations (see http://www.snap.uaf.edu/faq.php#faq_2). Precipitation data (Figures 9, 11, 13, and 15) are from the SNAP historical dataset using PRISM and data from the Climate Research Unit (CRU; http://www.cru.uea.ac.uk) datasets where PRISM data are unavailable.

Mean summer temperatures (June-August; Figure 8) show decadal variability and dramatic warming since 1990. Lowland regions have warmed more than the surrounding hills or mountains of the Alaska Range. Though some climate scenarios project greater rates of warming than others for interior Alaska (Figure 9) the trend of overall increasing air temperatures is projected to increase in the future.

There was a large amount of interdecadal variability in summer precipitation (1906–2006) (Figure 10) but no significant trends in interior Alaska (Wendler and Shulski, 2009). Modeling scenarios for future summer precipitation in the area (Figure 11) result in decadal variability in precipitation with the IPCC B1 and A1B scenarios projecting slightly wetter conditions and the IPCC A2 scenario projecting an overall drying. In general, the climate of interior Alaska is dry, receiving 29 cm of annual precipitation (Jorgenson et al., 2001; Wendler and Shulski, 2009). As a consequence, a few large convective summer storms can have a substantial impact on any season's precipitation total.

Figure 12 depicts decadal mean winter temperatures for interior Alaska from 1910 to 2009. The results show a general trend of increasing winter temperatures since 1910. Wendler and Shulski (2009) report the greatest winter season warming in the months of December and January for their 1906 to 2006 records from a station near Fairbanks. The mean December-February warming since 2006 is 1.3°C (Wendler and Shulski, 2009). Future climate scenarios project an increase in December to February temperatures between the 2010 to 2019 and 2030–2039 decades with consistent agreement across three IPCC model scenarios (Figure 13).

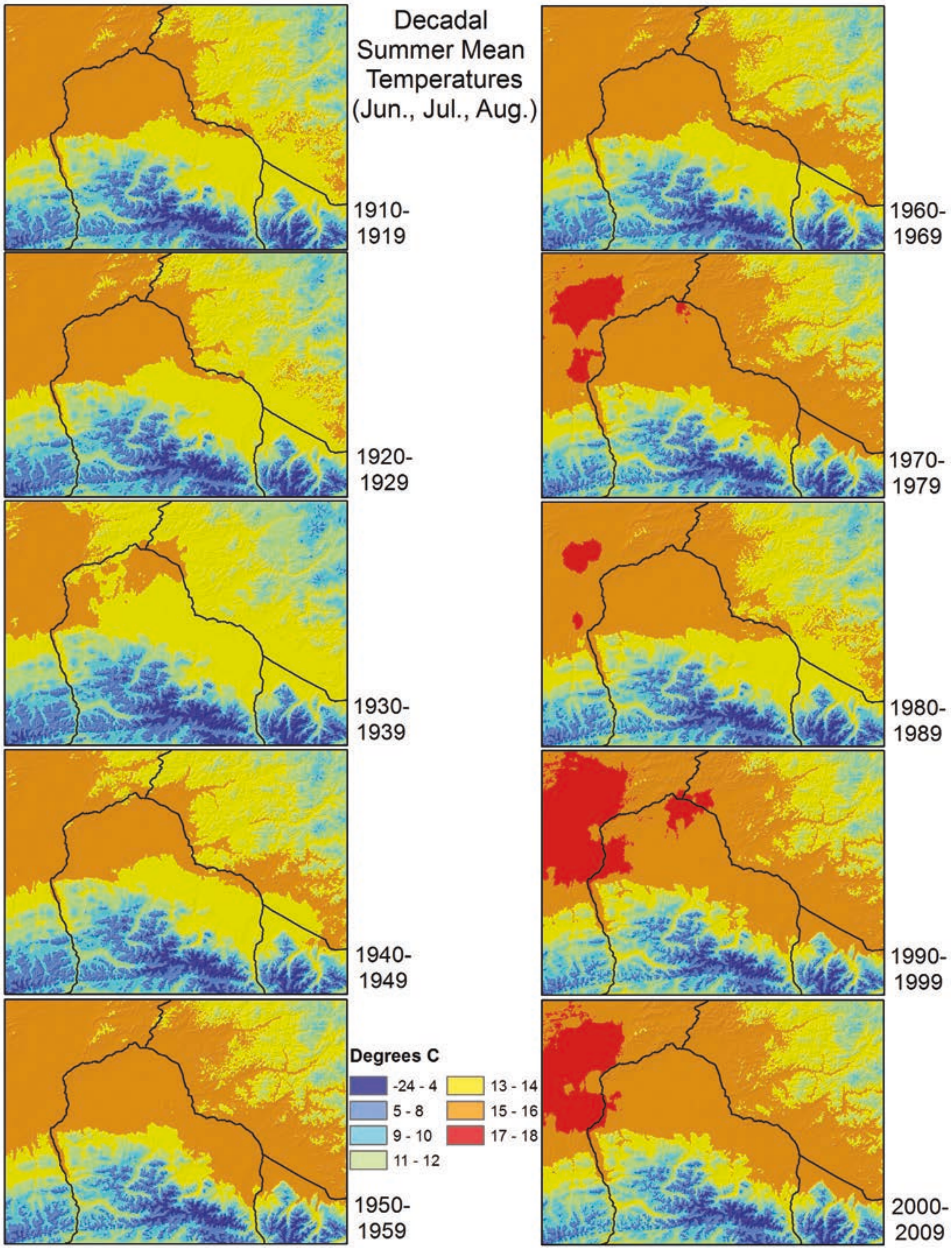

Figure 8

Decadal summer (June-August) mean temperatures for Tanana Flats and surrounding areas of interior Alaska.

Major road systems (Figure 1) are black.

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Winter season precipitation has decreased from 1910 to 2009 (Figure 14). The future winter season is expected to be shorter based on modeling efforts that simulate snow accumulation and melt over 30 years (1979–2009; Liston and Hiemstra, 2011) For interior Alaska, simulated results indicate a 4 cm decrease in precipitation and a 0.5°C drop in temperature during the snow-covered seasons. Forty percent of the annual precipitation arrived as snow in 2009 compared with forty-five percent in 1979. Over that 30 year period, snow arrived 8 days later and melted 9 days earlier, leading to a shortened snow season of ~17 days. Projections of future precipitation in the area based on the IPCC model scenarios (Figure 15) suggest winter precipitation totals are expected to be slightly lower while summer precipitation is not expected to change much (Figure 10). This regional and local scale of change is in contrast to the fact that GCMs typically project warmer temperatures lead to greater moisture in the atmosphere and, as a consequence, increased precipitation rates (Räisänen, 2008; Walsh et al., 2008).

Increasing temperatures are expected to have pronounced effects on soil and water biogeochemical processes in regions underlain by discontinuous permafrost (Osterkamp and Romanovsky, 1999). As the climate warms in both summer and winter, permafrost will continue its current warming trend (Romanovsky et al.,

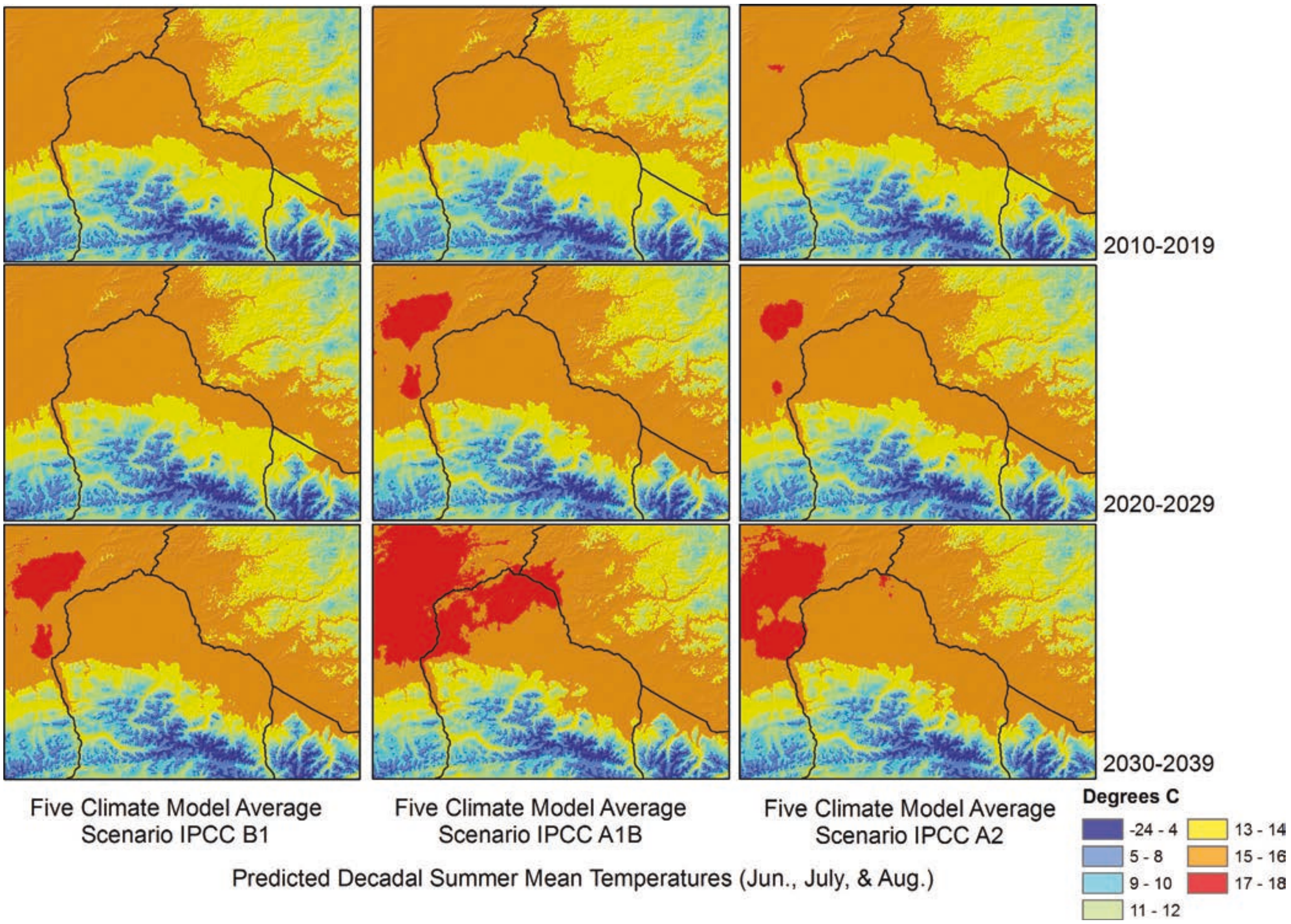

Figure 9

Downscaled projected decadal summer (June-August) mean temperatures for interior Alaska.

Major road systems (Figure 1) are black. Data are from the Scenarios Network for Alaska and Arctic Planning projected dataset which is derived from downscaled climate model simulations averaged from five climate models that perform well in Alaska (General Circulation Model version 3.1, European Centre Hamburg Model 5, Coupled Climate Model 2.1, Coupled Model 3.0, and Model for Interdisciplinary Research on Climate-medium resolution). B1, A1B, and A2 scenarios represent relatively low, intermediate, and high CO_2 emission futures (Solomon et al., 2007).

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2012), the active layer will become thicker, the lower boundary of permafrost will become shallower and the areal extent of permafrost will decrease. These structural changes will affect components of the surface water and energy balances. As the active layer thickens there is greater storage capacity for soil moisture and lags are introduced into the hydrologic response times to precipitation events. When permafrost is close to the surface, the stream and river discharge peaks are higher and base flow is lower (i.e., streams are "flashier"). If permafrost degrades, connectivity between surface and subsurface water flowpaths can increase (Walvoord et al., 2012). Depending on the hydraulic gradient, more infiltration of surface water or exfiltration of groundwater occurs when permafrost extent decreases. This has significant impacts at both large and small scales by reducing summer runoff and increasing the yearly proportion of winter runoff as deeper flowpaths become a larger component of subsurface flows (Douglas et al., 2013).

5. Carbon sources and sinks in interior Alaska

It is estimated that northern circumpolar permafrost soils contain 1,672 billion metric tons of organic carbon (Tarnocai et al., 2009) which accumulated slowly over thousands and tens of thousands of years. Roughly 60% of this carbon is believed to be located in the circumpolar permafrost zone and an estimated 277 billion metric tons of the northern soil carbon pool is associated with peatlands (Schuur et al., 2008). Discontinuous permafrost in interior Alaska is composed partially of "yedoma-type" permafrost which has a carbon content of 2–5%, up to 30 times greater than what is typically present in thawed mineral soils (Zimov et al., 2006a, 2006b; Douglas et al., 2011; Kanevskiy et al., 2011). This yedoma permafrost formed during the Pleistocene when windblown loess was repeatedly deposited to the soil surface to create ice-rich syngenetic permafrost (Shur and Jorgenson, 2007; Douglas et al., 2011). Yedoma deposits are believed to contain almost one quarter of the northern permafrost soil carbon pool (Tarnocai et al., 2009). Permafrost in interior Alaska has also been formed from alluvial and aeolian deposition (syngenetic type), peat accumulation (syngenetic and quasi-syngenetic types) and climate variations (epigenetic type).

Northern high latitude terrestrial soils have acted as carbon sinks over millennia as plants soak up CO_2 from the atmosphere, partially decompose, and are buried in soils. However, a recent increase in high severity fires, an increase in permafrost thaw, and projected changes to the soil and vegetation composition due to

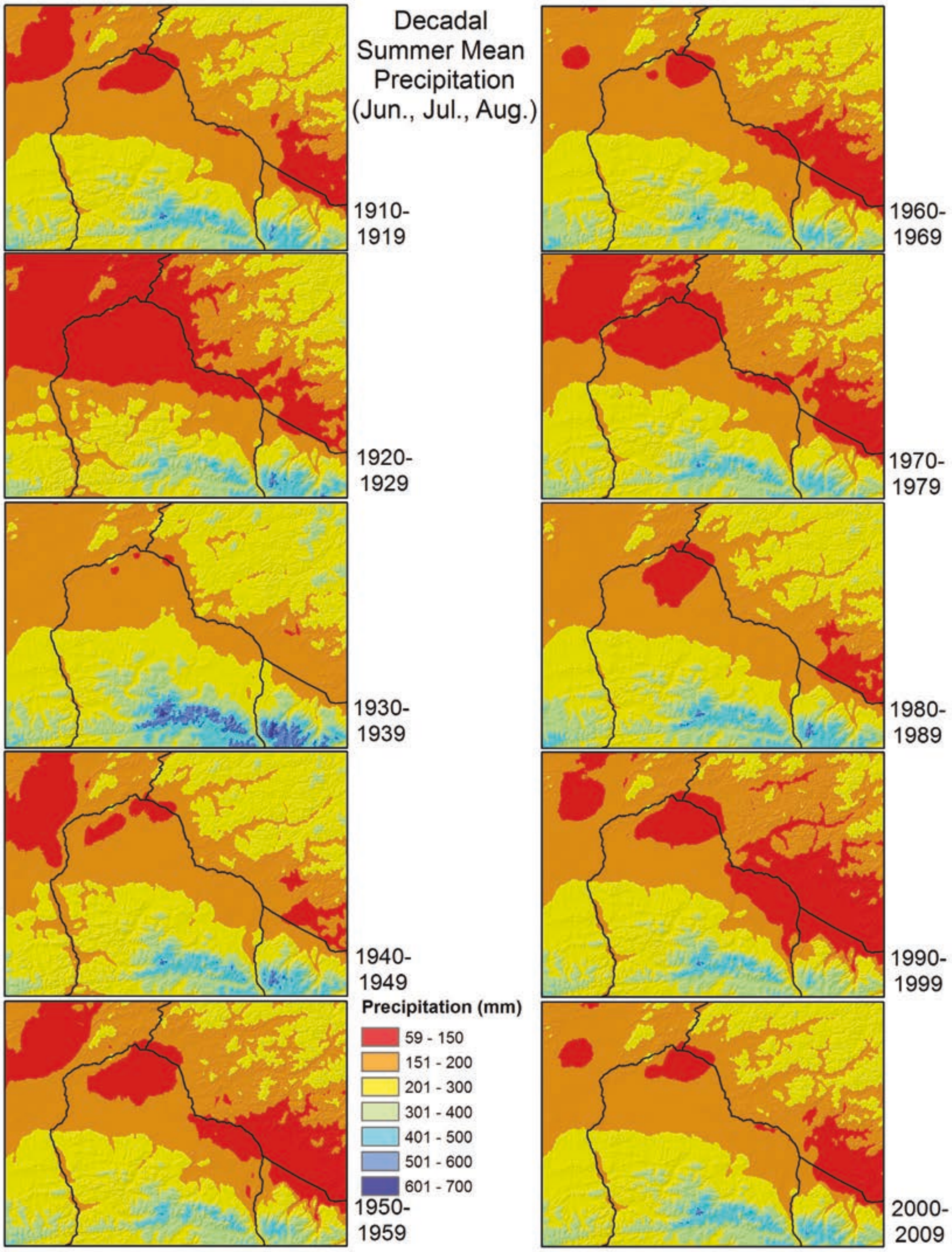

Figure 10

Decadal summer (June-August) total precipitation for interior Alaska.

Major road systems (Figure 1) are black. Data are from the Scenarios Network for Alaska and Arctic Planning historical dataset derived from downscaled climate data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; http://prism.oregonstate.edu) and Climate Research Unit (CRU; http://www.cru.uea.ac.uk) datasets.

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climate warming will likely lessen this sequestering capability (Hayes et al., 2011). A larger concern is that permafrost thawing will yield increased carbon emissions from arctic and subarctic landscapes as permafrost degrades, providing a positive feedback to climate warming (Frey and Smith, 2005; McGuire et al., 2009; Koven et al., 2011; Schaefer et al., 2011; Schuur et al., 2013). Further, carbon emitted from thawing permafrost is several thousand years old, which essentially introduces a "new" carbon source to the atmosphere.

To identify the current inventory of carbon sinks in interior Alaska boreal ecosystems we separated the estimates available for carbon pools into aboveground, belowground, and soil C (Table 5). We also converted CH_4 and CO_2 fluxes reported in the literature into units of mg/m^2/day to calculate fluxes from a variety of ecosystem types in interior Alaska for comparisons across studies (Table 6). To compare carbon fluxes between CO_2 and CH_4 the molar mass of each molecule was taken into account. Most of the CH_4 fluxes are close to 0 given the large relative percent error for calculations based on flux measurements (Table 6). Bogs, moderately thawed soils, collapse-scar bogs/floating mats, and black spruce forest are all net carbon stores (see Table 6),

Table 5. Carbon stocks in aboveground and belowground biomass for representative interior Alaska ecosystem types

Cells are left blank if data are not available for that particular parameter.

Ecosystem type	**Soil TOC (mg/ha)**	**N**[1]	**Aboveground biomass C production (g/m^2–y)**	**±**	**N**[1]	**Belowground biomass (fine root) C production (g/m^2–y)**	**Reference**[3]
Black spruce lowland mean	513	36	113	11	4	232	A, B, C, D
Mixed forest	81	43					C, D
White Spruce	120	27	366	78	4	248	A, B, C
Deciduous:	72	34	526	102			C, D, E
Quaking Aspen			656	65	2	276	A, D
Paper Birch			470	8	3		A
Balsam Poplar			552	49	3	4386	A
Collapse scar peat (bog)	752	2					F

[1] Number in the population

[2] References:

- A) Van Cleve and Viereck, 1983
- B) Ping et al., 1997
- C) Johnson et al., 2011
- D) Laganière et al., 2011
- E) Gower et al., 2001
- F) Jones et al., 2013

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but they can shift to sources on interannual timescales (Euskirchen et al., 2014). Alteration from one state to another with permafrost thaw (i.e., black spruce forest to collapse-scar bog) can lead to a short-term (years to centuries) net source of carbon in the form of mostly methane. However, these areas can switch to a net sink on the order of many centuries to millennia (O'Donnell et al., 2012b). The stability of these ecosystems is tied to preservation of permafrost and/or protection from disturbance. If permafrost thaws, bogs can turn to fens or they can dry as subsurface water drains away from the wetland. When permafrost under black spruce forest degrades or burns the capacity of the CO_2 sink will likely decrease, but will eventually (over decades) increase as peat production increases following thaw and forest regeneration occurs following burn.

Annual aboveground biomass production is lowest in black spruce ecosystems with less than one quarter of the annual biomass production of its deciduous counterparts and one third of the biomass production of white spruce ecosystems (Van Cleve and Viereck, 1983; Yarie and Billings, 2002). Consequently, CO_2 uptake is low under slow-growing black spruce forests, but respiration (and thus CO_2 release) also slows as organic carbon accumulates in the soil. Minimal release of CH_4 occurs from these forests and in some cases they can act as a carbon sink (Euskirchen et al., 2010). Fire may alter this source-sink dynamic (Bond-Lamberty et al., 2007).

Despite the greater aboveground productivity of the deciduous tree species soil carbon storage is greater in black spruce forests. This is attributed to poor soil drainage which slows decomposition, inhibits sub-surface moisture run-off, accumulates more organic matter, and promotes the upward migration of the active layer

Table 6. A summary of results from studies that present methane and carbon dioxide fluxes from common ecosystems present in interior Alaska

The carbon equivalents are given for the CH_4 and CO_2 fluxes. CO_2 values represent net ecosystem exchange (NEE). Negative values indicate carbon uptake and positive values indicate flux to the atmosphere. Cells are left blank if data are not available for that particular parameter.

Ecosystem type	Northern high latitude lake CH_4 ebullition (Tg/year)	Northern high latitude lake CH_4 diffusion (Tg/year)	CH_4 flux (mg/m^2/day)	+/– (mg/m^2/day)	C flux from C(mg/m^2/day)	CO_2 flux (mg/m^2/day) NEE[1]	+/ (mg/m^2/day)	C flux from CO_2 (mg/m^2/day)	References[2]
Lakes	2.2±1.5	0.12±.02	73	6	55				A, B, C
Bog (permafrost)			2	4	1.5	–7161	2836	–2261	A, B
Moderately thawed soils			42	30	31.5	–11299	4118	–3568	A, B
Collapse-scar Bog/ floating mat			290	117	217	–9362	1547	–2956	A, B
Black spruce forest			–0.02	0	–0.02	–140000	99	–44210	A, B, D

[1] NEE: net ecosystem exchange

[2] References:
A) Bellisario et al., 1998
B) Wickland et al., 2006
C) Walter et al., 2008
D) Ueyama et al., 2006

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during steady state climate conditions. Permafrost protects soil carbon from further decomposition and functions as a soil C stabilization mechanism. Carbon stocks in the top meter of black spruce lowland soils average 513 mg/ha, 85% more than what is found in deciduous forest soils (Table 5) and 75% more than white spruce soils. The amount of carbon in black spruce lowland soils is only rivaled by that of collapse-scar bogs, which average 751.7 mg C/ha (Jones et al., 2013). This suggests permafrost degradation, particularly in lowland terrains, can increase belowground carbon storage in the long term (centennial to millennial timescales) due to more anaerobic soil conditions that slow decomposition (O'Donnell et al., 2012b).

The amount of carbon uptake and biomass production in different ecosystem types depends on the complex interplay between successional stage, water balance, nutrient availability, and topography. For example, in black spruce forests where CO_2 fluxes were measured, hot and dry summer conditions resulted in half the CO_2 uptake of the previous growing season (Ueyama et al., 2006). Similar conditions in a black spruce forest in interior Alaska resulted in a net flux of CO_2 to the atmosphere (Euskirchen et al., 2014). In a recent study of boreal black spruce soils, Wickland and Neff (2008) showed temperature and moisture are the main controls on carbon mineralization rates. Further, they found carbon mineralization rates were highest in soils from a well-drained site absent of permafrost. The extensive groundcover of mosses in the boreal forest contributes significantly to overall productivity, between an estimated 25% and 14% total aboveground net primary productivity in permafrost and permafrost-free upland forests (Turetsky et al., 2010). Flux estimates for moss dominated areas range from 24 to 77 grams carbon/m^2/yr (Oechel and Van Cleve, 1986; Bisbee et al., 2001). This moss accumulation effectively buffers soils from atmospheric climate perturbations because of its high porosity, low thermal conductivity, and high water holding capacity (Rydin and MacDonald, 1985; O'Donnell et al., 2009; Turetsky et al., 2010; Turetsky et al., 2012). Topography can play a major role in carbon dynamics due to its role in controlling lateral and vertical movement (and, thus, availability) of water (Grant, 2004; Kane et al., 2005; 2010).

Thermokarst lakes are significant CH_4 "hot spot" sources relative to other landform types with the highest CH_4 fluxes occurring along actively thawing lake margins where highly labile carbon previously frozen in permafrost undergoes anaerobic decomposition and releases CH_4 through diffusive or ebullition (bubbling) processes (Walter et al., 2007a; 2007b; 2008; Shakhova et al., 2010). Much of the carbon released from thermokarst lakes is old, having been locked in the permafrost since the Holocene or Pleistocene (Walter et al., 2006). Lakes can also emit a substantial amount of CO_2 (Kling et al., 1991; Cole et al., 1994; Algesten et al., 2004). Although lakes are large CH_4 and CO_2 sources, they also have the potential to sequester carbon as lake sediments and peat accumulate with time (Jones et al., 2012; Walter-Anthony et al., 2014).

Evidence from Siberia suggests lake drainage can inhibit further lake expansion which may also limit carbon fluxes to the atmosphere from these systems (Van Huissteden and Dolman, 2012). Lake drainage

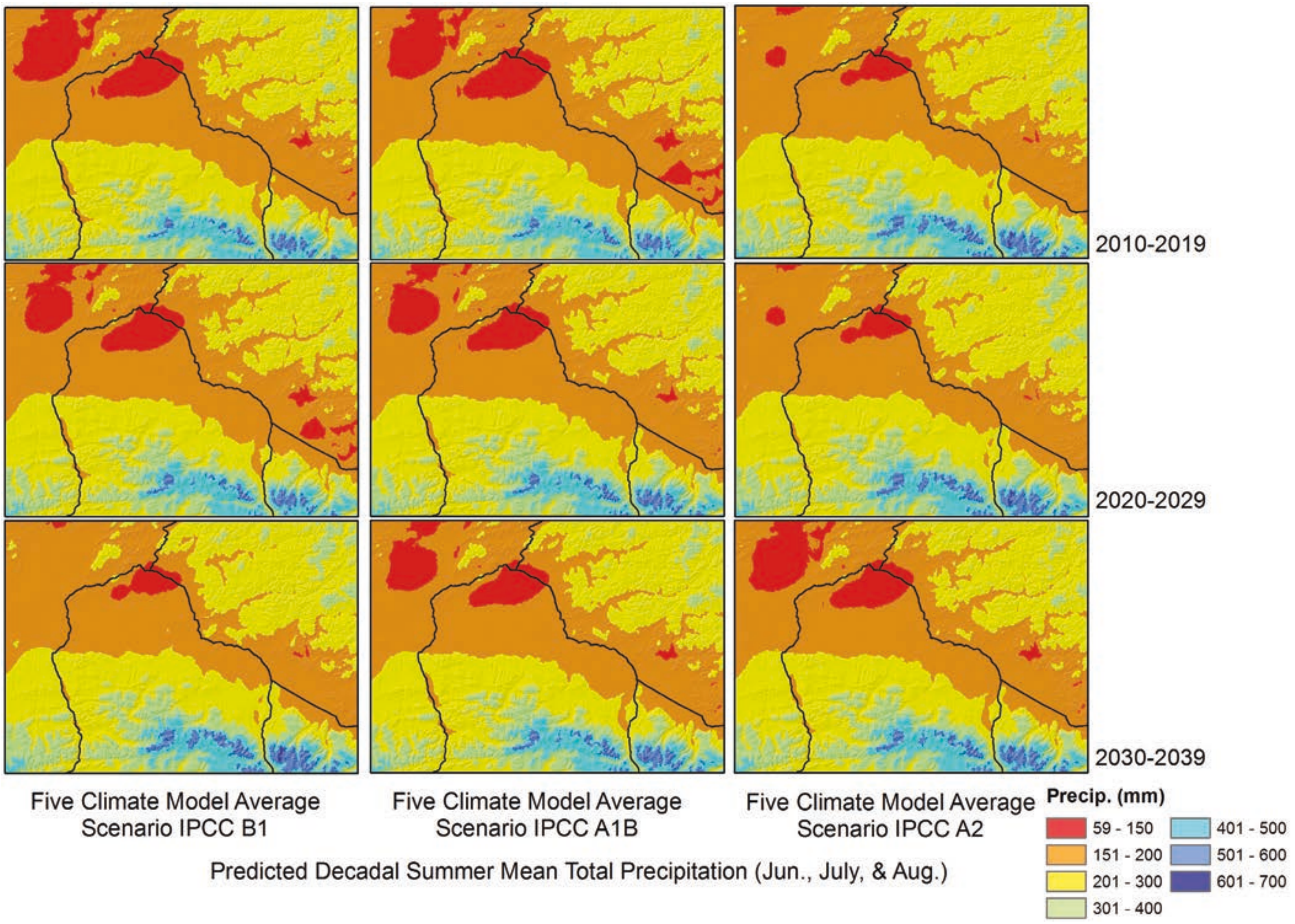

Figure 11

Downscaled projected decadal summer (June-August) average total precipitation for interior Alaska.

a. Major road systems (Figure 1) are black.

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can also result in peat accumulation within a matter of decades, and the accumulation of peat in these basins act as a carbon sink (Jones et al., 2012) and has the potential to offset losses of CH_4 and CO_2, but only after centuries to millenia. A recent data and modeling analysis of the radiative forcing of thermokarst lakes since the last deglaciation has revealed that despite being CH_4 sources, thermokarst lakes as a whole became carbon sinks ~5,000 years ago (Walter-Anthony et al., 2014). Thermokarst lakes are ephemeral on the landscape, lasting only 2,000–3,000 years before they drain or partially drain, which in both cases promotes peat accumulation (Jones et al., 2012; Walter-Anthony et al., 2014). This is because in the deep study lakes in yedoma permafrost, the water at the bottom is cold enough to limit decomposition of organic matter. The authors warn, however, that under a warmer climate that cannot support permafrost, these lakes will disappear where no aquitard is otherwise present. Then the lake sediments and soil carbon will decompose and be emitted to the atmosphere. In regions where lakes are expected to persist even in the absence of permafrost, warmer temperatures will result in lake terrestrialization, which will increase carbon uptake (Roach et al., 2011).

5.1 Potential changes in carbon sources and sinks with permafrost thaw

The amount of carbon released as a result of thawing permafrost depends partly on the quality and quantity of the organic substrate in the previously frozen soil (Schuur et al., 2008). Temperature, moisture content, nutrient availability, and oxygen availability are the primary controls on carbon transformation rates in soils. The primary control on the release of CH_4 or CO_2 to the atmosphere is the degree of soil saturation where anaerobic conditions result in CH_4 production and dry aerobic conditions result in CO_2 production.

In uplands, permafrost thaw can lead to the creation of topographic lows that can result in the formation of ponds, lakes or other standing water bodies. In well-drained uplands, permafrost thaw can lead to surface water drainage or soil drying (Schuur et al., 2008). Wetter conditions in uplands would favor carbon sequestration by *Sphagnum* mosses and sedges (Trumbore and Harden, 1997; Turetsky et al., 2000; Camill et al., 2001). Permafrost thaw in drier uplands would increase afforestation, lower albedo, and increase decomposition and the release of soil C (Goulden et al., 1998; Stieglitz et al., 2000; Lloyd et al., 2003; as cited in Camill, 2005).

In lowlands, surface inundation of organic-rich material leads to enhanced CH_4 production. Complete permafrost degradation leads to drastic changes in surface moisture conditions as permafrost thaw triggers ground subsidence and surface inundation, which, in turn, results in a shift to completely anaerobic soil

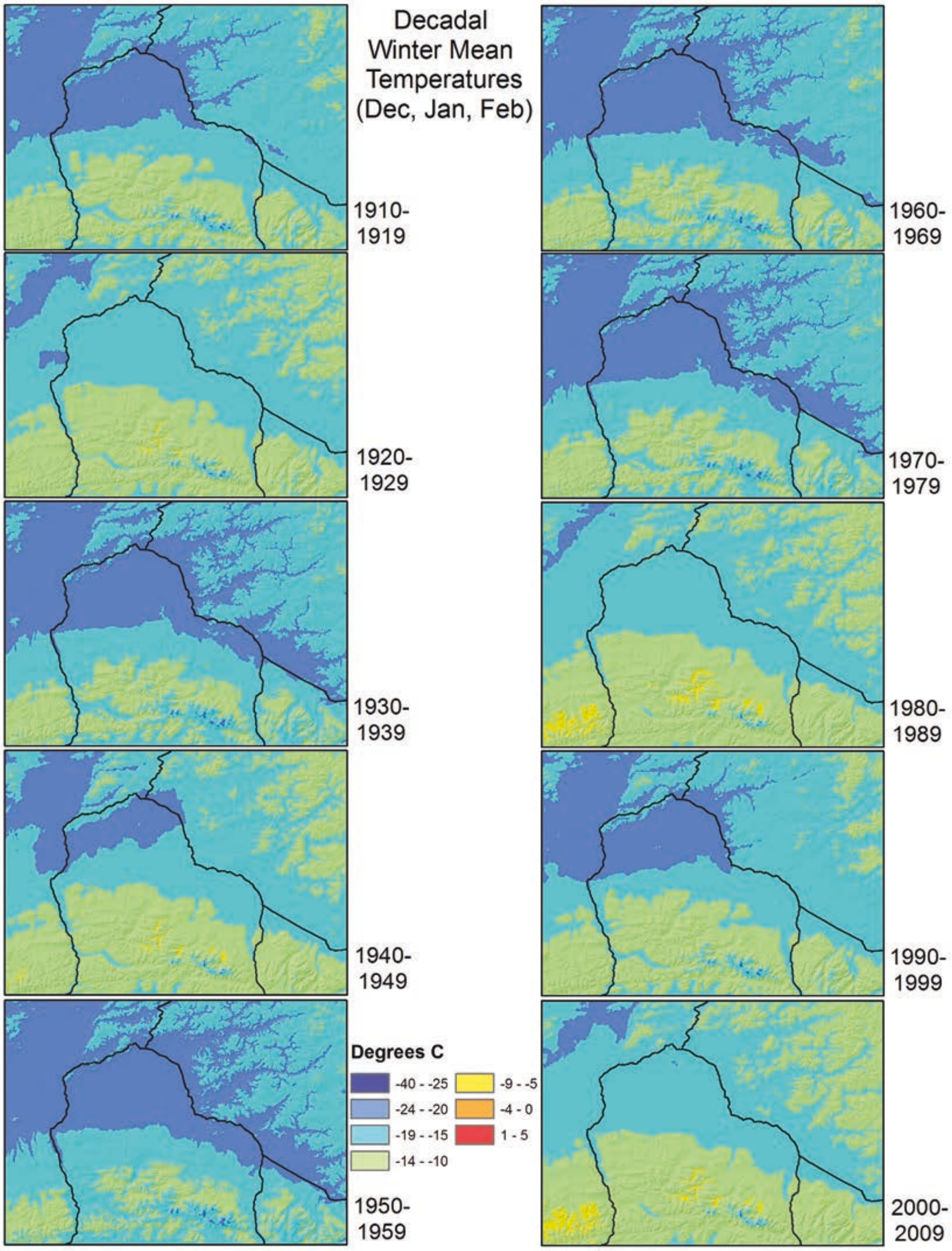

Figure 12

Decadal winter (December-February) mean temperatures for interior Alaska.

Major road systems (Figure 1) are black.

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conditions. Depending on the degree of ice richness of the permafrost this ground subsidence can result in the formation of collapse-scar bogs, fens or thermokarst lakes. Talik formation can lead to significant groundwater input and the minerotrophic conditions that support fen vegetation. Methane emissions from collapse-scar bogs and fens increase as both a function of surface inundation from permafrost thaw and increased NPP, which is related to both temperature and nutrient availability (Bubier et al., 1995; 2005). In a metadata analysis of methane emissions from global wetlands, Turetsky et al. (2014) found that sites with permafrost emitted the least amount of methane, and that fens on average emit more than bogs. Plant species composition is a strong indicator of methane flux, with a greater presence of graminoid taxa linked to higher emissions (Bubier, 1995; Couwenberg et al., 2011).

Quantifying CH_4 release from collapse-scar bogs and fen systems is difficult because of their unevenly distributed, episodic ebullition and diffusive fluxes. Nonetheless, CH_4 emission from collapse-scar bogs and fens formed after permafrost thaw is typically an order of magnitude greater than pre-thaw (Table 6). Generally, they are only sources of carbon to the atmosphere for a few years to decades following thaw, but

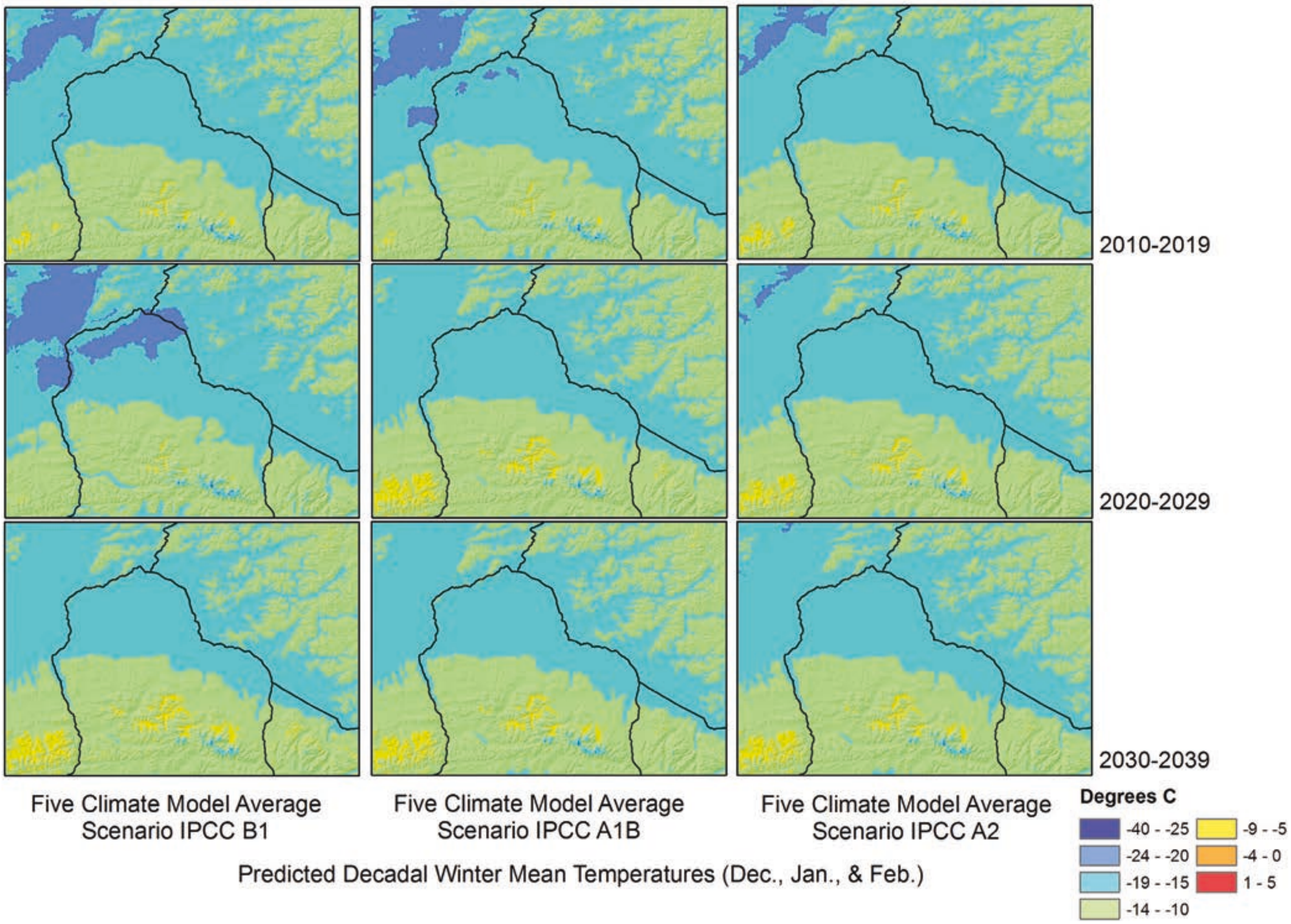

Figure 13

Downscaled projected decadal winter (December-February) mean temperatures for interior Alaska.

Major road systems (Figure 1) are black.

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on longer decadal to centennial timescales they remain net carbon sinks. Their sink capacity can be weaker depending on interannual climate patterns (i.e., weaker during warm, dry conditions; O'Donnell et al., 2012b; Euskirchen et al., 2014). The modern age of the carbon released from these systems suggests CH_4 production, for the most part, is not tied to the consumption of old, previously frozen carbon. More recently, however, emissions from thawing permafrost, thus older methane, accounted for up to 22% of flux from methane released during senescence in a collapse-scar bog in interior Alaska (Klapstein et al., 2014). Similarly, a permafrost peatland incubation study showed a major source of respired carbon (in the form of CO_2) came from just above the active layer, which is an older carbon source (Dorrepaal et al., 2006). The permafrost thaw was not complete and only resulted in active layer thickening. Active layer thickening without complete collapse of deeper permafrost is thought to be a likely scenario for much of the discontinuous permafrost zone and is consistent with observations (Zhang et al., 2005a; 2005b). However, collapse-scar bogs usually expand laterally and represent a catastrophic collapse of the ground surface (Jorgenson and Osterkamp, 2005; O'Donnell et al., 2011). For both uplands and thermokarst lakes, permafrost thaw has resulted in elevated releases of CH_4 (uplands) and CO_2 (lakes) to the atmosphere (Walter et al., 2006; Zimov et al., 2006a; 2006b; Schuur et al., 2009). In both ecosystems a significant fraction of the carbon released to the atmosphere was found to be old permafrost carbon with radiocarbon ages ranging from the Holocene to the late Pleistocene. Thus, both collapse-scar bogs and thermokarst lakes initially pulse large quantities of carbon to the atmosphere, but over longer millennial timescales become carbon sinks as peat accumulates (O'Donnell et al., 2012b; Jones et al., 2013; Walter-Anthony et al., 2014).

In a well-drained upland tundra ecosystem in central Alaska, minimally thawed areas showed the lowest release of old carbon while deeper thaw resulted in a higher proportion of old carbon loss. Areas thawed over the last 15 years were net carbon sinks because increased plant growth offset carbon losses (Schuur et al., 2009). The release of old carbon was 78% higher in locations that had thawed decades earlier compared to sites where thaw had been minimal. This suggests long-term and continuous carbon loss from these upland areas as permafrost continues to thaw (Schuur et al., 2009). The greater carbon loss with increasing time since thaw in this upland site may reflect redistribution of water as the site thaws or, perhaps, more extensive vertical thawing (i.e., a deeper active layer). Ground subsidence due to melting of ground ice features may result in

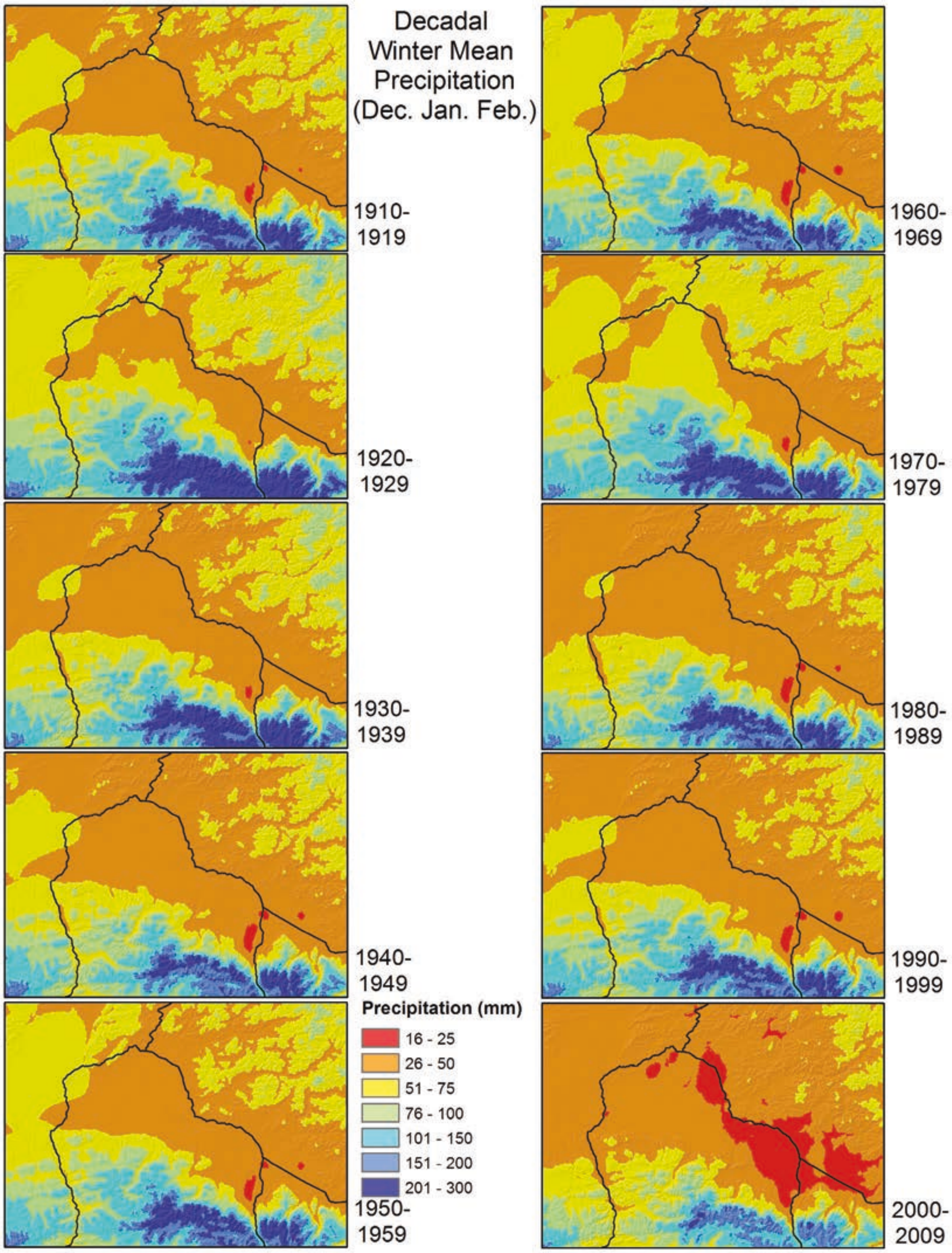

Figure 14

Decadal winter (December-February) total precipitation for the Tanana Flats and surrounding areas of interior Alaska.

Major road systems (Figure 1) are black.

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increased surface wetness initially but surface drying occurs as adjacent areas continue to thaw, followed by gully formation, which allows water to drain away. This process ultimately leads to the death of peat-forming mosses, an increase in shrub growth (Osterkamp et al., 2009), and the initiation of forest succession. Over time, the landscape is initially a carbon source (drying and thawing), then a slow sink as aboveground biomass accumulates (forest development).

5.2 Observed carbon fluxes from terrestrial ecosystems as a result of permafrost thaw

Arctic and sub-arctic watersheds export much of their carbon as DOC flushed out of surface vegetation and soils during spring melt (Macdonald and Yu, 2006; Raymond et al., 2007; Cai et al., 2008a). Roughly 60% of the annual DOC export from arctic and sub-arctic rivers occurs within the two months following snow melt and ice breakup (Finlay et al., 2006; Raymond et al., 2007), and this carbon is of modern age (Guo and Macdonald, 2006; Neff et al., 2006). Spring melt is also associated with what is typically the largest surface

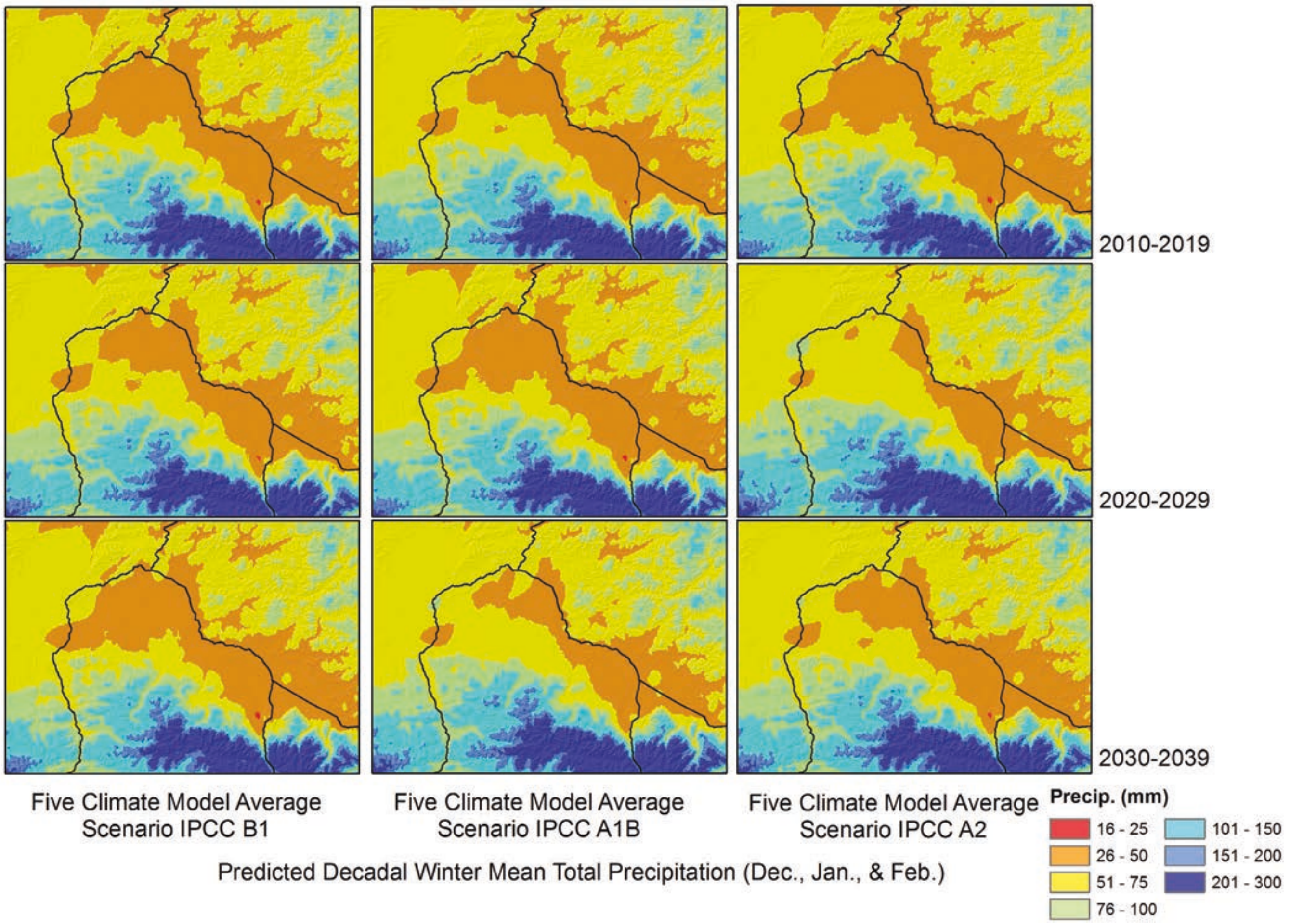

Figure 15

Downscaled projected decadal winter (December-February) average total precipitation for the Tanana Flats and surrounding areas of interior Alaska.

Major road systems (Figure 1) are black.

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water loads of other nutrients (like nitrogen) and trace metals (Rember and Trefry, 2004) as melt water interacts with surface soil and vegetation (McNamara et al. 2008; Frey and McClelland, 2009). The timing of spring melt has been moving earlier (Stone et al., 2002) but the potential ramifications of an earlier melt for nutrient export fluxes or composition are largely unknown.

Changes in permafrost extent will likely have profound impacts on the export of DOC, dissolved inorganic carbon (DIC), and particulate organic carbon (POC) from terrestrial ecosystems into nearby waterways (Guo et al., 2007). The Arctic Ocean comprises only 1% of the global ocean volume but receives over 10% of the global river transported terrestrial dissolved organic matter (DOM) because arctic rivers contain extremely high DOM concentrations (Dittmar and Kattner, 2003). Striking relationships between DOC concentrations in permafrost versus permafrost-free watersheds are observed in western Siberia, where higher DOC concentrations occur in permafrost-free watersheds with large peatlands (Frey and Smith, 2005). If the watersheds become permafrost-free by 2100, DOC export in the West Siberia region could increase 46% (Frey et al., 2007). However, positive relationships between higher DOC concentrations and greater permafrost area have been reported elsewhere and this is ascribed to shallow flow paths of water through organic-rich soils where permafrost is present (Petrone et al., 2006). Meanwhile, other studies have shown decreased DOM export with increasing permafrost degradation after a brief increase in export initially following thaw in Alaska (MacLean et al., 1999; Striegl et al., 2005; 2007; Petrone et al., 2006; 2007), the Yukon Territory (Carey, 2003), and central Siberia (Kawahigashi et al., 2004; Prokushkin et al., 2007). This is thought to occur as a result of increased adsorption of DOM in newly exposed underlying mineral soils (Frey and McClelland, 2009).

As the climate warms, thawing of permafrost in peatland-rich regions could lead to the release of old carbon to streams and rivers (Smith et al., 2005) because subsurface flow would increase (Frey and McClelland, 2009). This would lead to an increase in the export of carbon from permafrost terrains. The hydraulic conductivity of peat can vary widely (Holden and Burt, 2003) but is generally considered low (Reynolds et al., 1992). Low hydraulic conductivities increase the residence time of water in peatlands and increase the potential for decomposition and leaching of DOM, but this also slows the rate of export from peatlands to nearby waterways. DOM production is low in slowly draining, anoxic peat soils because the anoxic conditions reduce decomposition rates (Moore and Knowles, 1989; Stutter et al., 2007). Another factor contributing to DOC production is the recalcitrance of the organic material in the peat, because vascular fen vegetation is more labile than *Sphagnum* moss.

Studies in West Siberian peatlands report that permafrost limits dissolved organic matter exports but DOC values rise in watersheds as peatland cover increases (Frey and Smith, 2005; Frey and McClelland, 2009). Striegl et al. (2007) report potential decreasing exports of dissolved organic matter from watersheds undergoing permafrost thaw due to the adsorption of DOM by newly exposed mineral soils. Thus, depending on permafrost extent and the percentage of mineral versus peat soil encountered by flows through watersheds, DOC export could either increase or decrease with permafrost thaw.

The lability of DOC appears to vary depending on time of the year. DOC lability is substantially higher during the spring freshet (Cooper et al. 2005; Guo and Macdonald, 2006; Holmes et al., 2008) and is largely recalcitrant during low-flow summer periods (Dittmar and Kattner, 2003; Holmes et al., 2008; Frey and McClelland, 2009). This can be explained by the short residence time, colder temperatures, and low microbial activity during spring melt. In contrast, increased thaw in the summer results in less surface water interaction with sediments and increased incorporation of slower flowing water at depth. Greater export of decaying terrestrial organic matter into the Arctic Ocean has been suggested to increase pCO_2 levels, resulting in outgassing (Shakhova and Semiletov, 2007). This was observed along the Laptev and East Siberian Seas by Anderson et al. (2009) who determined an excess of DIC equal to 10^{12} g C is expected to outgas to the atmosphere due to terrestrial organic matter decay.

Although permafrost thaw results in the release of labile organic carbon, the age of DOC exported from arctic streams has been found to be of recent origin (Benner et al., 2004; Neff et al., 2006). Studies from the Kolyma River basin (Neff et al., 2006), the Yenisey, Lena, Ob' in Siberia, and the Mackenzie and Yukon Rivers in Canada and Alaska (Raymond et al., 2007) show relatively young ^{14}C ages of DOC during the spring freshet but DOC ages increase in the late summer as thaw depth increases. This suggests as climate warms and thaw depths increase the potential to export older carbon to the Arctic Ocean will increase.

5.3 Carbon sources and sinks in interior Alaska lands – a synthesis

We have synthesized the results from numerous studies on ecosystem dynamics and the carbon cycle in the boreal biome into three schematic diagrams to illustrate carbon sources, sinks and fluxes in interior Alaska boreal ecosystems (Figures 16–18). The purpose of these diagrams is to provide information, based on the most current scientific studies, that can be used as a predictor of how lowland and upland ecosystem vegetation and soil processes are expected to respond to climate warming and their subsequent carbon cycle impacts.

Our synthesis assumes climate change in interior Alaska will lead to shorter, warmer winters and warmer summers with increased evapotranspiration and longer growing seasons. We first provide the initial response of the different ecotypes to these changes in the climatic regime. In the diagrams the long thin arrows denote a physical process that disturbs the system like forest degradation or aggradation and landscape flooding or drying. These include natural disturbances like permafrost degradation or the impact of fire on soil thermal properties and human- caused disturbances like vegetation clearing (Nicholas and Hinkel, 1996), prescribed burns, or altering landscape hydrology through infrastructure development. In each of the three diagrams the boxes denote ecosystem processes where we provide the best estimate for magnitude and directionality of CO_2 or CH_4 fluxes, which are represented by the short, bold arrows.

Mixed forests (Figure 16) slowly accumulate an organic layer as the forest develops toward a needle leaf forest (Euskirchen et al., 2010), resulting in a modest sink for both CO_2 and CH_4 as organic matter is stored belowground. Depending on the ice content of the permafrost, thaw can result in ponding that will turn the forest from a CO_2 sink to a source and to a large CH_4 source. Pond or lake drying in the lowlands can result in lake terrestrialization and eventually bog formation, which results in a drawdown of CO_2 in the atmosphere through peat accumulation and provides a small CH_4 source through anaerobic decomposition. These bogs can form through permafrost degradation or drying of lakes or ponds.

Needle leaf forests can undergo a shift to mixed forest when severe fire burns the surface organic material down to the mineral soil (Johnstone and Kasischke 2005; Barrett et al., 2011), or when fire return intervals are more rapid than the time required for succession to conifers. Severe fires are associated with major CO_2 emissions and a major disruption in permafrost thermal stability. Permafrost degradation that causes surface wetting after major fires can transform a needle leaf forest into a bog which leads to CO_2 storage and enhanced CH_4 emission. If permafrost degradation increases groundwater input into a wetland, a fen can form, and fens are typically larger CH_4 sources than bogs (Turetsky et al., 2014).

In lowland ecosystems without permafrost (Figure 17), like some areas in Tanana Flats, with a well-drained substrate, forests are usually deciduous or transitioning to mixed type in areas of more advanced stages of succession. Conversely, a mixed forest will emerge if a fen dries out and a drying lake system can turn into a fen, leading to enhanced CO_2 uptake and CH_4 release. Fire disturbance will result in a short-term (i.e., several decades) pulse of CO_2 and CH_4 to the atmosphere, but regeneration of the deciduous forest that

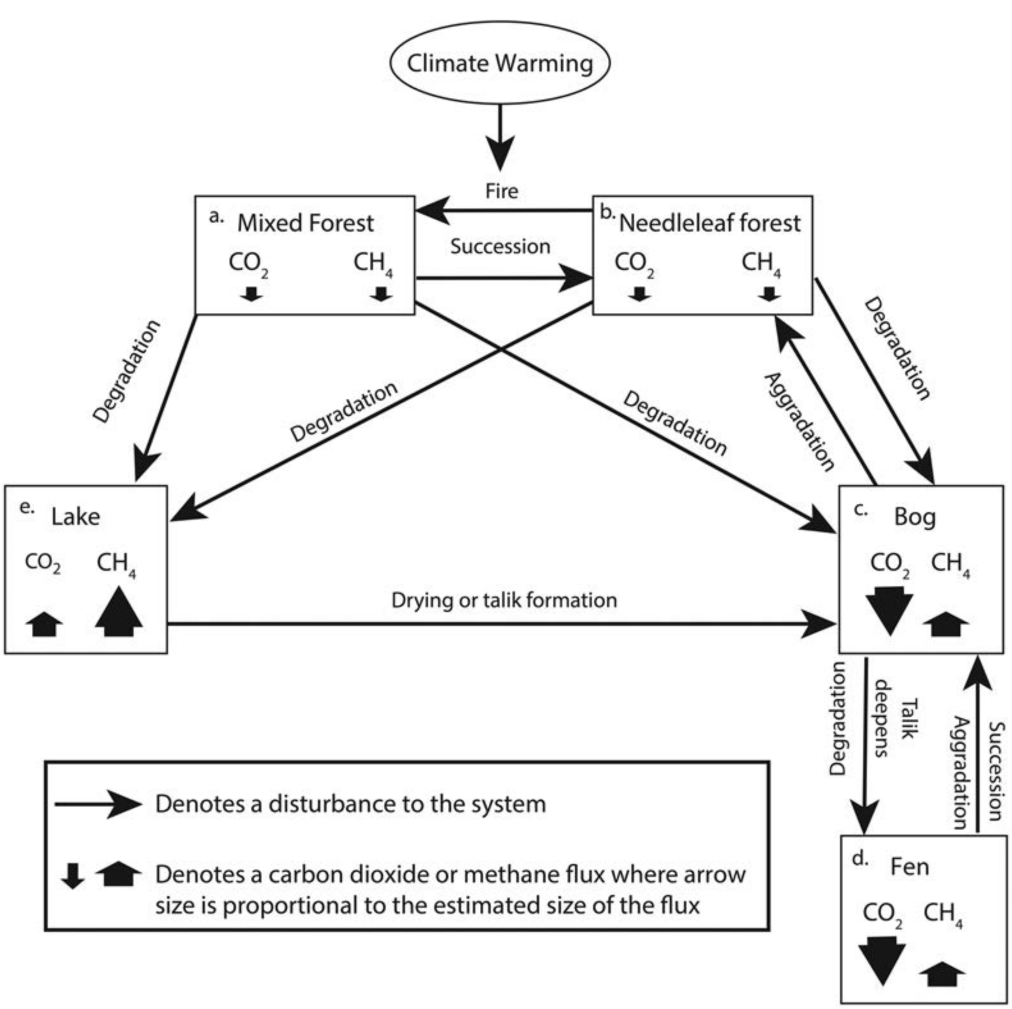

Figure 16

Schematic diagram of present and likely future carbon cycle changes in lowland ecosystems with permafrost.

Climate Change impacts (as outlined in the text) are expected to include warmer summers, warmer winters, and a longer growing season. Natural system disturbances include permafrost thaw, fire, and vegetation changes while human caused disturbances include fire, clearing, impact cratering, vehicle/boat traffic, soil erosion, or the removal of the surface organic layer. References are as follows: a) Euskirchen et al. (2010) and Zhuang et al. (2003); b and c) Bellisario et al. (1998) and Wickland et al. (2006); d) Turetsky et al. (2008); e) Algesten et al. (2004), Walter et al. (2006), and Walter et al. (2008).

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emerges post-fire is a CO_2 sink. Flooding inundates forests, leading to tree mortality, which can result in fen formation, a large source of CH_4 and a moderate CO_2 sink.

Upland ecosystems (Figure 18) are characterized by sloping terrain that tends to prevent the emergence of lakes, fens or bogs except in valley bottoms, which often comprise localized lowland type ecosystems. The boreal forest provides a small but steady CO_2 sink whether or not permafrost is present and if there is no disturbance by fire, invasive species, or human activities. Immediately following disturbance, the uplands become a CO_2 source, but with increasing time since disturbance the forests in upland regions become a substantial CO_2 sink. This is the case for both non-permafrost and permafrost settings when the permafrost remains thaw stable. If the permafrost thaws, CO_2 and CH_4 can be emitted from the soils but if/when the forest continues to grow the area becomes a CO_2 sink.

5.4 Challenges to interior Alaska land management due to climate warming

The hydrological and ecological shifts associated with thawing permafrost, particularly on the Tanana Flats lowlands, are expected to have large consequences for state and federal government land management and carbon itemization activities. Unfortunately, change will not come uniformly across the landscape. As a consequence, land and facilities planning will require a better knowledge of locations where change is expected to occur. As discussed previously, there are three major processes that can rapidly alter ecosystems: fire, altered nutrient dynamics due to either permafrost thaw or altered hydrogeology, and human and biological disturbance. These three processes are expected to respond to climate warming and in some cases will amplify the effects of climate warming at a variety of scales.

Increasingly, compounding disturbances are providing a challenge for landscape resource managers. An example: a significant fire occurs in a forest previously affected by physiological stress due to a decades-long drought from warmer summer air temperatures or decreased precipitation. The result of these compounding disturbances is a more severe fire than would be predicted or expected if the fire consumed a healthy forest.

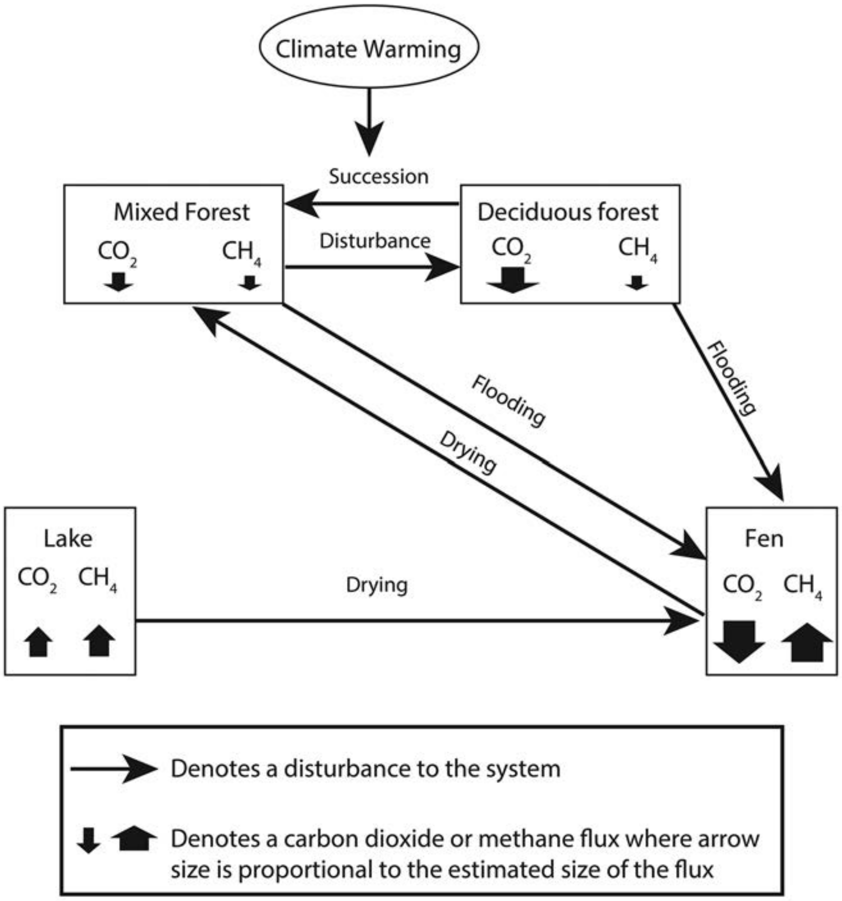

Figure 17

Schematic diagram of present and likely future carbon cycle changes in lowland ecosystems without permafrost.

Climate Change impacts (as outlined in the text) are expected to include warmer summers, warmer winters, and a longer growing season. Natural system disturbances include fire and vegetation changes while human caused disturbances include fire, clearing, impact cratering, vehicle/boat traffic, soil erosion, or the removal of the surface organic layer. Details on vegetation types can be found in Jorgenson et al. (1999).

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If drought conditions persisted during post fire succession then the recovery would take longer and soil development and forest succession would be limited. Another example of compounding disturbances would be that more severe fires, occurring more often, consume highly combustible drought-stressed white spruce and this would lead to yet larger and more expansive fires.

5.5 Anticipated impacts of a warming climate on interior Alaska ecosystems

Based on our assessment of the major carbon cycle processes that govern carbon sources and sinks in the boreal biome of interior Alaska, we have identified three main ecological responses to climate warming that will have the most profound influences on lands in interior Alaska over the next 100 years. These ecological changes will have a pronounced effect on the carbon cycle at a range of spatial and temporal scales.

First, climate-driven permafrost degradation will radically reorganize upland and lowland hydrology and vegetation by altering soil flow paths and changing subsurface flow through the partial degradation or wholesale loss of permafrost (Hinzman et al., 1991; 1998; Kane et al., 1991; Woo, 2000; Douglas et al., 2013). Changes in surface water extent due to permafrost degradation are linked to local ground subsidence either when near-surface ice-rich permafrost thaws (the area may still be underlain by continuous permafrost) or when permafrost is degraded and a connection develops between surface and sub-permafrost water. In the latter case, the local hydraulic gradients determine whether or not the area becomes drained or flooded. As a consequence, the permafrost extent also largely controls vegetation.

The ecosystem and its hydrologic and thermal regimes are dynamically coupled such that neither can be fully understood without considering the other (Harvey, 1988; Chahine, 1992; Hinzman et al., 1996; 2003b). Regions of discontinuous permafrost in interior Alaska and Canada have shown both increases and decreases in surface water spatial extent linked to permafrost degradation (Jorgenson et al., 2001; Romanovsky and Osterkamp, 2001; Osterkamp, 2005; Osterkamp and Jorgenson, 2006; Osterkamp, 2007). Near-surface soil moisture exerts a strong influence on the amount of heat transferred into soils, especially if the ground surface is covered by moss. Changes in the soil thermal regime will significantly alter the lateral and vertical distribution of permafrost. Groundwater recharge, runoff and water storage will be altered considerably as a result of permafrost thaw and this will increase the fraction of subsurface flow in annual river runoff. These changing hydrologic regimes will alter the seasonality and biogeochemistry of Alaskan river discharge by increasing the winter portion and, in some locations, may increase total discharge (Peterson et al., 2002).

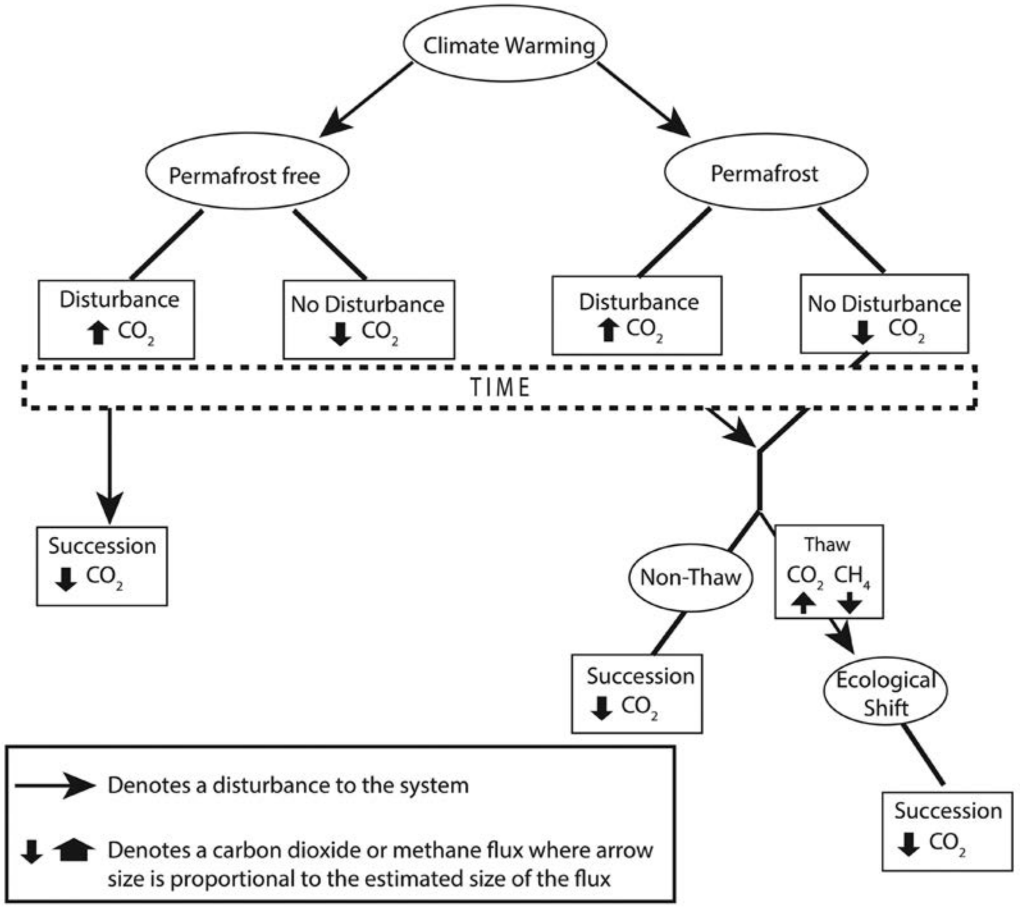

Figure 18

Schematic diagram of present and likely future carbon cycle changes in upland ecosystems with and without permafrost.

Climate Change impacts (as outlined in the text) are expected to include warmer summers, warmer winters, and a longer growing season. Natural system disturbances include permafrost thaw, fire, and vegetation changes while human caused disturbances include fire, clearing, impact cratering, vehicle/boat traffic, soil erosion, or the removal of the surface organic layer. Fluxes and ecosystem dynamics are based on the work of Chapin et al., 2010; Euskirchen et al., 2010; and Wolken et al., 2011.

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Second, a longer growing season (Høye et al., 2007) will favor some species over others and this will alter vegetation composition, abundance, and productivity (Wolken et al., 2011), soils (Grosse et al., 2011) and their associated controls on the boreal carbon cycle. Due to the heterogeneous nature of soils, vegetation, and permafrost extent in interior Alaska and the potential feedbacks between a longer growing season and ecosystem respiration it is difficult to determine at a regional scale whether the longer growing season will result in a greater CO_2 or CH_4 sink (Euskirchen et al., 2006; Parmentier et al., 2011).

Third, decreased soil moisture and humidity will increase the number, areal extent, and severity of fires, which will alter permafrost stability and the fate of carbon. Fire is the single largest element of rapid change in boreal ecosystems. Carbon stored in aboveground and belowground biomass can be rapidly combusted and emitted to the atmosphere. Numerous studies have shown that the most severe fires burn vegetation down to the mineral soil and this can alter the post-fire ecological trajectory and permafrost thermal stability. Of equal importance is whether the fire-return interval is short enough to limit forest succession and soil development processes from sequestering carbon.

Forecasting ecological responses to climate warming is complicated by soil type, precipitation, surface and ground water hydrology, vegetation, slope, aspect, fire prevalence, and the thermal state of permafrost. Therefore, to reduce uncertainty in future projections and refine planning on lands in interior Alaska the ecosystem hydrologic and thermal regimes need to be linked. This will be accomplished by combining climate modeling with soil and snow pack thermal measurements and modeling with high-resolution digital elevation models and remote sensing measurements. From this, spatially explicit, high-resolution landscape change predictions can be developed. If/where they can be linked to ecosystem drivers such as hydrologic, soil, or vegetation processes a geospatial predictor of carbon source and sink processes can be developed. Synthesizing these measurements and model projections with remotely sensed tools will allow for broader application to a greater variety of terrains. This is of particular utility because much of the land areas in interior Alaska are roadless and remote. Anticipated ecosystem changes in interior Alaska will likely have severe ramifications for how and where State and Federal government agencies should direct resources to promote land use sustainability or ecological preservation or restoration or to address invasive plants.

6. Summary and recommendations

Based on the information presented herein and guided by the results from numerous studies focused on the boreal biome, permafrost dynamics, climate warming impacts, and the carbon cycle, we provide the following recommendations for land management activities and future research needs. The purpose of these recommendations is to identify a series of measurements, management tools, and planning activities that we believe can help to integrate ecosystem processes into estimates of carbon sources and sinks in ecosystems of interior Alaska. With this information carbon management activities can be prioritized in terms of work effort and cost.

1) We anticipate the following changes will occur to the ecosystems of interior Alaska with climate warming:
    - Flows in interior Alaska rivers are likely to change as the growing season expands, more precipitation falls as rain, and the timing of spring melt and major precipitation events are altered. Changing seasonality will alter the two major hydrologic transitions: spring melt and fall freeze-up. Since spring melt is a short period of time when large fluxes of DOC and other organic material are exported from watersheds, a shift to an earlier spring melt runoff may affect ecosystem processes. It is not expected that spring peak flows will increase substantially, but warmer summers and enhanced convective activity could yield localized intense storms and flooding. The U.S. Army Corps of Engineers' Chena River Flood Control project and recreation area were designed with permafrost in mind so the facilities and infrastructure are not likely to be substantially affected by climate warming impacts to permafrost in the near future.
    - Based on projections for the Yukon River (Walvoord and Striegl, 2007), of which the Tanana River is the largest tributary, we would expect to see an increase in the groundwater contribution to streamflow. Summer season flows in the Tanana River are expected to become greater as run-off from increased glacier melt feeds headwater streams (Woo et al., 2008). This could lead to greater flooding risk for the city of Fairbanks and for other infrastructure in the Tanana River floodplain. The effect of an altered groundwater regime on watershed carbon dynamics is not well understood. An increase in low carbon glacial flows would be expected to lead to a decrease in glacial river carbon concentrations but may not change the total fluxes from terrestrial ecosystems.
    - The Tanana Flats (lowland) ecosystem is susceptible to major surface hydrological, vegetation and permafrost changes with climate warming. Due to the intricate feedbacks between permafrost, soils, hydrology, and climate change many of these processes and regime changes are difficult to predict and thus are not easily integrated into future planning scenarios. One consequence could be a continued decrease in the areal extent of permafrost as climate warms and fires become larger and deeper, resulting in greater localized groundwater upwelling zones. Many of the lowland deciduous forests could disappear and turn into a matrix of bogs and fens, depending on localized hydrogeology. The thermal state of permafrost and fire severity will play major roles in controlling whether this ecosystem is a carbon source or sink.
    - Locations like the southern Tanana flats lowland, where lands contain a mixture of upland and lowland ecosystems, will likely exhibit complicated and potentially unpredictable ecosystem responses to climate warming. Rocky moraines may be affected by increased fire frequency and this could lead to the reduction of white spruce forests while loess deposits are vulnerable to collapse due to the thawing of ice-rich permafrost (Toniolo et al., 2009). With warming, permafrost degradation, and the likely drying of the Tanana Flats fire will play a major role in controlling the carbon balance and vegetation succession of these ecosystems. This could seriously impact the infrastructure (roads, buildings, railway, and bridges) planned in this area by the Army, the Air Force, the Alaska Railroad, and the State of Alaska.
    - Upland ecosystems are expected to incur increased fire frequency (disturbance) and a general reduction in black and white spruce forests, drying of south-facing slopes, and a loss of permafrost on north-facing slopes as a response to climate warming (Woo, 2000). This will likely lead to enhanced near term CO_2 emissions from this ecosystem that will be reduced over time with post-fire vegetation succession and transition to deciduous forest.
    - Spring melt runoff is the time of the year when more than half of the annual DOC exports leave arctic and sub-arctic watersheds, predominately as modern age carbon and as carbon associated with particulates, surface organic matter, other nutrients (like nitrogen), and trace metals. The spring melt event is expected to be shifted earlier in the spring but the nature and amount of this large pulse flow of aquatic carbon is not expected to change. Importantly, once snow cover departs the system has a longer drying period that both stresses trees and enhances chances of fire (Wolken et al. 2011).
2) Estimated recovery times following disturbance (as required in Environmental Impact Statements, Environmental Assessments, and future planning scenarios) are likely to become less predictable in the future. Climate-driven changes in the timing of seasonal transitions, the amount of warming by season, and the fraction of wet versus dry precipitation will alter hydrologic, soil thermal, and vegetation

regimes, making prediction of recovery difficult. Locations where a specific forest or soil type is currently climatically viable will be altered and this will limit our ability to predict the carbon cycle response(s) to disturbance. This will challenge the flexibility and adaptability of government agency land use and infrastructure development planning. When multiple disturbances are acting on a system at the same time (compounding disturbance) predicting the response becomes even more difficult.

3) Fire management activities should be focused toward encouraging low to medium severity fires to maintain carbon storage in upper soils, preserve permafrost thermal stability, and prevent the loss of deep soil carbon during and immediately following larger, more severe fires. Though this is a difficult, expensive, and resource-intensive management action to undertake, it could have the greatest impact on preserving carbon in surface soils, promoting vegetation growth, and maintaining permafrost stability. In addition, by more actively managing fires, the potential for loss of infrastructure and lives will be greatly minimized because the potential for prescribed burns or natural fires to grow out of control will be minimized. A series of GIS-based decision support tools could be created and used to identify which locations are most susceptible to high severity fires and what management actions to take. This is explained in greater detail in item #8 below.
4) Where possible, minimize loss of the insulative and organic rich surface soil and vegetation layer during disturbance (fire, road building, vertical or horizontal infrastructure development). This will help prevent permafrost degradation and will reduce the loss of soil carbon stores. In some select locations it may lead to permafrost formation or at least increased thaw stability (Shur and Jorgenson, 2007).
5) Where activities such as airboat travel, road clearing, infrastructure development, or prescribed burns occur, we encourage minimizing the rapid draining or horizontal movement of water across the surface and shallow subsurface. Channeling, draining, or ponding water destroys the thermal balance of the surface and subsurface and this can lead to thermokarst and/or the liberation of surface and subsurface carbon. This is of particular concern in permafrost lowland areas where regional gradients are low (i.e., sub-meters of elevation change over kilometers of distance). At some of these sites permafrost provides a subsurface aquitard or aquiclude that maintains surface water. If/where this surface water leaves channels or encounters higher hydraulic conductivity soils the wetland areas supported by horizontal flows may be drained.
6) We recommend establishing a series of long-term monitoring sites representing a varied amount of time since disturbance and diverse types of disturbances to follow landscape succession and soil processes over time. These sites would be located on lands overseen by the different landusers/stakeholders in the interior Alaska boreal forest. The frequency and types of measurements made would support the user's specific needs with respect to land management requirements, ecosystem processes, and carbon itemization efforts. The most likely candidate locations for this work would be areas of similar landscape and ecosystem type that burned at different times/decades. This would allow a comparison across time since disturbance. Repeat imagery analysis and remote sensing tools could help identify and measure change over time at these long-term sites. Remote sensing could also be applied toward extrapolating measurements at one landscape type to similar regions in the interior Alaska boreal forest and elsewhere. There are a variety of remote sensing measurements that could be used to help manage fire and human disturbance and to predict where permafrost degradation could have the largest impacts on soil thermal and hydrologic stability and carbon cycle processes. The difficulty in accessing remote field sites and the wide variety of landscape and ecological processes occurring across interior Alaska make it likely that the most useful approach could be remote sensing and repeat imagery analyses verified with focused ground-truth efforts.
7) More studies are needed during the two major seasonal transitions (winter-spring melt-summer and summer-fall-winter freeze up). The spring melt period is associated with what is typically the largest yearly redistribution of water (snow melt) across the landscape, and this occurs in a period of days to weeks. The fall to winter transition is a key part of soil and vegetation dynamics in the boreal biome as ground freezing is initiated and snow starts to cover the landscape. It is expected that the timing of these seasonal transitions will change in the future and it is likely that the soil, vegetation, and carbon cycle will respond to the changing seasonality and the longer growing season.
8) We encourage the development of GIS-based decision support tools to help State and Federal government land managers decide where to construct or modify existing facilities and to identify what level of winter and summer vehicle traffic different terrains/landscapes can support as those landscapes change in response to climate warming. Soil characterization information, permafrost extent, wetlands delineation, and climate projection information could be used to identify locations where human activities or climate impacts are at most risk of altering permafrost thaw stability. High resolution digital elevation measurements (such as from ground-based or airborne light distance and ranging (LiDAR)) can be combined with wetland and soil moisture information to predict locations where thermokarst or subsidence is most likely to alter surface hydrology. This would be of particular utility in lowland regions where ground surface elevations may only change by a meter or two over many kilometers of distance. Fire is the single largest ecological disturbance in the boreal biome and provides the most rapid means of altering

ecosystem source and sink compartments for carbon. A multi-faceted geospatial decision support tool could also provide guidance on where to apply focused management actions such as prescribed burns and where to site infrastructure or invasive species management strategies.

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Contributions

- TAD, MCJ, CAH, and JRA wrote the manuscript.
- MCJ did the carbon sink calculations.
- CAH oversaw the climate projection integration into the work and created most of the Figures.
- JRA participated in project discussions and oversaw project financial management.

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14. ABSTRACT

Boreal ecosystems store large quantities of carbon but are increasingly vulnerable to carbon loss due to disturbance and climate warming. The boreal region in Alaska and Canada, largely underlain by discontinuous permafrost, presents a challenging landscape for itemizing carbon sources and sinks in soil and vegetation. The roles of fire, forest succession, and the presence/absence of permafrost on carbon cycle, vegetation, and hydrologic processes have been the focus of multidisciplinary research in boreal ecosystems for the past 20 years. However, projections of a warming future climate, an increase in fire severity and extent, and the potential degradation of permafrost could lead to major landscape and carbon cycle changes over the next 20 to 50 years. To assist land managers in interior Alaska in adapting and managing for potential changes in the carbon cycle, this paper was developed incorporating an overview of the climate, ecosystem processes, vegetation, and soil regimes. The objective is to provide a synthesis of the most current carbon storage estimates and measurements to guide policy and land management decisions on how to best manage carbon sources and sinks. We provide recommendations to address the challenges facing land managers in efforts to manage carbon cycle processes. The results of this study can be used for carbon cycle management in other locations within the boreal biome which encompasses a broad distribution from 45° to 83° north.

15. SUBJECT TERMS

Carbon cycle, boreal ecosystem, Alaska, climate warming, permafrost, land management

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