Ecological Applications, 27(5), 2017, pp. 1383–1402

Historical and projected trends in landscape drivers affecting carbon dynamics in Alaska

Neal J. Pastick,[1,2,12] Paul Duffy,[3] Hélène Genet,[4] T. Scott Rupp,[5] Bruce K. Wylie,[6] Kristofer D. Johnson,[7] M. Torre Jorgenson,[8] Norman Bliss,[9] A. David McGuire,[10] Elchin E. Jafarov,[11] and Joseph F. Knight[2]

[1]*Stinger Ghaffarian Technologies (contractor to the U.S. Geological Survey), Sioux Falls, South Dakota 57198 USA*
[2]*Department of Forest Resources, University of Minnesota, St. Paul, Minnesota 55108 USA*
[3]*Neptune and Company, ,Lakewood, Colorado 80215 USA*
[4]*Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, Alaska 99775 USA*
[5]*International Arctic Research Center, Scenarios Network for Alaska and Arctic Planning, University of Alaska Fairbanks, Fairbanks, Alaska 99775 USA*
[6]*U.S. Geological Survey, Earth Resources Observation and Science Center, Sioux Falls, South Dakota 57198 USA*
[7]*Northern Research Station, U.S. Department of Agriculture Forest Service, Newtown Square, Pennsylvania 19073 USA*
[8]*Alaska Ecoscience, Fairbanks, Alaska 99709 USA*
[9]*ASRC Federal InuTeq (contractor to the U.S. Geological Survey), Sioux Falls, South Dakota 57198 USA*
[10]*U.S. Geological Survey, Alaska Cooperative Fish and Wildlife Research Unit, University of Alaska Fairbanks, Fairbanks, Alaska 99775 USA*
[11]*Computational Earth Sciences, Los Alamos National Laboratory, Los Alamos, New Mexico 87545 USA*

Abstract. Modern climate change in Alaska has resulted in widespread thawing of permafrost, increased fire activity, and extensive changes in vegetation characteristics that have significant consequences for socioecological systems. Despite observations of the heightened sensitivity of these systems to change, there has not been a comprehensive assessment of factors that drive ecosystem changes throughout Alaska. Here we present research that improves our understanding of the main drivers of the spatiotemporal patterns of carbon dynamics using in situ observations, remote sensing data, and an array of modeling techniques. In the last 60 yr, Alaska has seen a large increase in mean annual air temperature (1.7°C), with the greatest warming occurring over winter and spring. Warming trends are projected to continue throughout the 21st century and will likely result in landscape-level changes to ecosystem structure and function. Wetlands, mainly bogs and fens, which are currently estimated to cover 12.5% of the landscape, strongly influence exchange of methane between Alaska's ecosystems and the atmosphere and are expected to be affected by thawing permafrost and shifts in hydrology. Simulations suggest the current proportion of near-surface (within 1 m) and deep (within 5 m) permafrost extent will be reduced by 9–74% and 33–55% by the end of the 21st century, respectively. Since 2000, an average of 678 595 ha/yr was burned, more than twice the annual average during 1950–1999. The largest increase in fire activity is projected for the boreal forest, which could result in a reduction in late-successional spruce forest (8–44%) and an increase in early-successional deciduous forest (25–113%) that would mediate future fire activity and weaken permafrost stability in the region. Climate warming will also affect vegetation communities across arctic regions, where the coverage of deciduous forest could increase (223–620%), shrub tundra may increase (4–21%), and graminoid tundra might decrease (10–24%). This study sheds light on the sensitivity of Alaska's ecosystems to change that has the potential to significantly affect local and regional carbon balance, but more research is needed to improve estimates of land-surface and subsurface properties, and to better account for ecosystem dynamics affected by a myriad of biophysical factors and interactions.

Key words: Alaska; boreal forest; carbon dynamics; climate change; permafrost; succession; surface water; tundra; wetlands; wildland fire.

Introduction

At the simplest level, ecosystem carbon storage is a function of the inputs and outputs of carbon per unit time. However, the patterns and processes affecting

Manuscript received 20 January 2017; revised 9 February 2017; accepted 17 February 2017. Corresponding Editor: Yude Pan.
[12] E-mail: neal.pastick.ctr@usgs.gov

ecosystem carbon balance are complex and largely governed by interactive controls (e.g., disturbances) and regional climate, topography, biota, soil properties, and time (Chapin et al. 1996). These factors define the bounds of characteristics of ecosystems, in which ecosystem processes respond to and affect interactive controls, and changes in these driving factors can alter ecosystems and the sustainability of current properties (Dokuchaev 1879, Jenny 1941, Chapin et al. 2011). For instance, northern high-latitude ecosystems are experiencing major changes in structure and function as a result of climate change (Hinzman et al. 2005, Chapin et al. 2006, Wolken et al. 2011). Ongoing warming is projected to continue in northern high-latitude regions throughout the 21st century (Collins et al. 2013), which could further influence ecosystem disturbances and has the potential to remobilize vast quantities of carbon stored in these regions (Kasischke et al. 1995, McGuire et al. 2009, Schuur et al. 2015). Despite early warning signs and observed changes to ecosystems in Alaska, there has not been a comprehensive assessment of historical and future ecosystem carbon stocks and fluxes as driven by climate, topography, vegetation, wildfire, and permafrost dynamics in the state. Because of limited availability of inventory data in the region, such an assessment needs to rely on the use of ecosystem models. Therefore, it is critical for these models to represent the impacts of and interactions among environmental drivers to reproduce spatially heterogeneous dynamics of terrestrial and aquatic carbon stocks and fluxes.

Climate is the environmental factor that most strongly determines ecosystem processes and structure on broad geographic scales (Chapin et al. 2011). In Alaska, regional variations in climate explain broad-distribution patterns of disturbance, vegetation, and soil properties that influence carbon dynamics and stocks (Fig. 1). For instance, increased warming and widespread occurrence of drought have resulted in significant shifts in vegetation composition (mostly from shrub and tree expansion, Fig. 1(1)) and productivity in Alaska (Fig. 1(2); Goetz et al. 2005, Verbyla 2008, Beck et al. 2011). Analyses of in situ tree-ring data and satellite estimates of vegetation productivity show divergent responses in growth rates as a function of longitude and temperature, where increased growth rates were found at warming coastal sites in western Alaska and decreased growth rates were found in interior Alaska where ecological tipping points may have already been crossed (Beck et al. 2011, Juday et al. 2015). Warming over arctic tundra and forest–tundra ecotones has been linked to observations of increased plant productivity (Potter et al. 2013), and treeline and shrub expansion (Harsch et al. 2009, Myers-Smith et al. 2011) that is constrained by topography (Rupp et al. 2001). Further warming will likely change arctic and boreal vegetation and productivity that directly impacts carbon storage and turnovers, energy fluxes, ecosystem services, and, more broadly, climate feedbacks and disturbance regimes (Chapin et al. 2006, Euskirchen et al. 2009, Pearson et al. 2013).

Drainage conditions impact hydrology and soil moisture, which in turn results in different biogeochemical pathways of carbon release (Fig. 1(3); Schuur et al. 2009), vegetation composition and productivity (Christensen et al. 2004), and disturbance regimes in upland and lowland systems (Turetsky et al. 2011, Genet et al. 2013). Upland ecosystems, in the absence of impeding layers of permafrost or other substrate, typically have high rates of decomposition and mineralization, and thin surface organic layers due to dry aerobic conditions (Pastick et al. 2014). In contrast, flat, low-lying ecosystems are typically underlain by near-surface permafrost (Pastick et al. 2015*a*) leading to perched water tables and anaerobic conditions that slow rates of microbial decomposition, which results in the accumulation of large amounts of soil organic carbon in wetlands (Johnson et al. 2011, Jorgenson et al. 2013). However, the increased carbon accumulation could be offset by increases in methane production under saturated and anaerobic conditions (Zhuang et al. 2007, Johnston et al. 2014).

Permafrost warming and degradation in Alaska have increased in response to warming temperatures (Fig. 1(4); Grosse et al. 2011, Romanovsky et al. 2011), with large effects on regional hydrology (Walvoord et al. 2012), water balances (Riordan et al. 2006), vegetation composition and soil processes (Jorgenson et al. 2013), and local biogeochemistry (Fig. 1(5); Chapin et al. 2010). Declines in lowland lake extents have been associated with increased drainage due to permafrost thaw (Jones et al. 2011) and evaporative loss and paludification (Yoshikawa and Hinzman 2003, Roach et al. 2011). Ice-rich permafrost underlying lowland ecosystems is also vulnerable to degradation, which can result in soil subsidence and water impoundment that can result in conversions of forests to wetlands (Baltzer et al. 2014) and has the potential to increase methane emissions and carbon storage (Turetsky et al. 2007, Myers-Smith et al. 2008). In upland ecosystems, permafrost thaw can result in thermal erosion (Osterkamp et al. 2000) and improved drainage conditions that promote aerobic decomposition of soil carbon (Jorgenson et al. 2013). Further warming may lead to vast reductions in permafrost extents (Jafarov et al. 2012), exposing large amounts of previously frozen soil carbon and other nutrients to the atmosphere and hydrosphere (Abbott et al. 2015, Drake et al. 2015, Schuur et al. 2015), which may exacerbate climate warming (MacDougall et al. 2012). However, the spatiotemporal patterns of carbon dioxide (CO_2) and methane (CH_4) exchange between terrestrial ecosystems and the atmosphere are poorly understood because of the lack of information on the distribution and dynamics of land-surface and subsurface properties in Alaska.

Disturbance regimes directly and indirectly influence terrestrial ecosystem carbon stocks and dynamics (Chapin et al. 2010). Increasing wildfire extent has been linked to climate warming in Alaska (Fig. 1(6); Duffy et al. 2005, Hu et al. 2010, Young et al. 2016). In the last decade, annual burned area in boreal forests has doubled relative

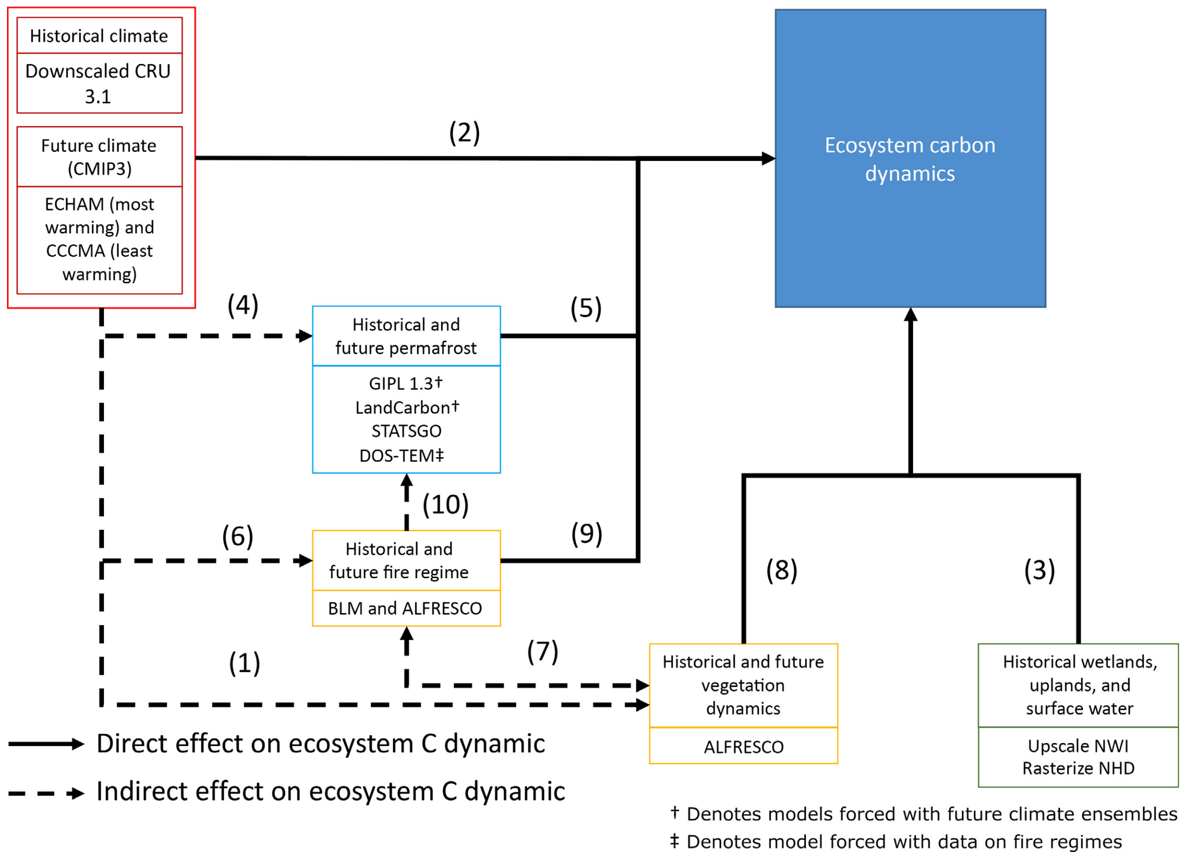

FIG. 1. Framework diagram showing relations between landscape factors that directly or indirectly impact ecosystem carbon stocks and fluxes in Alaska, USA, input data used for model calibration and initialization, and methods and models used in this assessment. Historical and projected climate, wetlands, upland, and surface water, permafrost, vegetation, and wildland fire data served as input into empirical and process-based models estimating carbon dynamics of aquatic and terrestrial ecosystems in Alaska. [Color figure can be viewed at wileyonlinelibrary.com]

to any of the previous four decades (Kasischke et al. 2010) and present fire frequency is unprecedented over the past 1200 yr (Kelly et al. 2013). In Alaska, wildland fires are one of the main causes of long-term fluctuations in the structure and function of ecosystems. Disturbances interact with biotic and landform effects to create distinct patches and mosaics of vegetation (Duffy et al. 2007), where patch size and fire severity affect seedling recruitment and capacity of regenerating vegetation to use pulse nutrients that accompany disturbance (Fig. 1(7); Rupp et al. 2000). Changes in vegetation communities and soil conditions also alter ecosystem carbon dynamics (Fig. 1(8); Johnstone et al. 2010) and disturbance regimes through effects on flammability and fuel loads (Fig. 1(7); Hély et al. 2000, Krawchuk et al. 2006). Increasing fire severity and frequency may not only lead to a shift in boreal forest composition and distribution (Barrett et al. 2011, Johnstone et al. 2011), but can result in large carbon loss to the atmosphere through combustion of above- and belowground carbon (Fig. 1(9); Balshi et al. 2007, Turetsky et al. 2011). Further warming will likely lead to an increase in tundra fires (Joly et al. 2012) that can contribute a substantial amount of greenhouse gases to the atmosphere (Mack et al. 2011) and induce land surface subsidence/collapse (Jones et al. 2015). Severe wildland fires can remove large amounts of insulating organic layers that are important for permafrost stability and distribution (Fig. 1(10); Yoshikawa et al. 2002, Johnson et al. 2013). Once these protective layers are removed, permafrost can become vulnerable to thaw (Jafarov et al. 2013, Nossov et al. 2013) and may never recover if organic matter does not reaccumulate and further warming occurs (Brown et al. 2015). How the complex interactions among climate, vegetation distribution, and soil conditions will determine the spatial and temporal patterns of fire regimes in response to projected climate change across boreal and arctic Alaska remains uncertain.

It is clear from recent research that complex interactions among environmental factors must be taken into account to accurately quantify ecosystem carbon stocks and fluxes and their response to projected climate change. Consequently, the goal of this paper is to provide an analysis of the main drivers influencing ecosystem carbon dynamics in Alaska, and to develop a more holistic understanding of the historical and projected environmental changes that will affect the fate of carbon sequestration in Alaska. We explore the following questions: (1) How has Alaska's temperature varied historically in space and time (1950–2013), and what is the range of projections in the 21st century? (2) What is the current distribution of uplands, wetlands, and surface waters in Alaska? (3) What is the current distribution of permafrost and associated active-layer thickness in Alaska, and how might permafrost distribution change in 21st century? (4) How has the fire regime in Alaska changed in recent decades (1950–2015), and how might vegetation distribution and fire regimes change in the 21st century? In addition to these questions, we further examine how well processes related to the historical distribution of permafrost properties are represented by a biogeochemical process-based model. We refer the reader to a recent U.S. Geological Survey (USGS) report (Zhu and McGuire 2016) and other manuscripts in this invited feature for quantification of historical and future carbon dynamics, as this paper focuses on landscape factors driving these dynamics.

Methods

Overview

A wide range of statistical, empirical, and process-based approaches, which make use of in situ observations, remote sensing data, and other geospatial data sets, were used to answer the overarching questions of this study. These techniques were used to analyze and/or develop Alaska-wide estimates of (1) historical and projected climatic variables (i.e., temperature, length of growing season, precipitation, solar radiation, and humidity/vapor pressure); (2) regional wetland, upland, and surface water extents; (3) historical and future permafrost distribution and active-layer thickness; and (4) projected changes in vegetation distribution as driven by fire and climate. The resultant data sets represent major drivers of carbon dynamics (Fig. 1) and served as validation or as inputs for a process-based model, the dynamic organic soil version of the Terrestrial Ecosystem Model (DOS-TEM; McGuire et al. 1992), that was used to simulate historical (1950–2009) and future (2010–2099) cycling of carbon and nitrogen through the soil and vegetation of Alaska's terrestrial upland and wetland ecosystems (Genet et al. 2016, He et al. 2016). Regional estimates of aquatic carbon fluxes (Stackpoole et al. 2016), which were not modeled by DOS-TEM, also relied on the historical climate, wetland, surface water, and permafrost data described in the following subsections.

Downscaled climate variables

Historical (Climate Research Unit, CRU TS 3.1; Harris et al. 2014) and projected (CMIP3) monthly surface temperature and precipitation were downscaled via the delta method (Hay et al. 2000, Hayhoe 2010) using PRISM (Parameter–elevation Relationships on Independent Slopes Model) 1961–1990 2-km resolution climate normals (monthly temperature and precipitation) as baseline climate (Daly et al. 2008; data *available online*).[13] These coarse-resolution anomalies were then interpolated to PRISM spatial resolution via a spline technique, and then added to (temperature) or multiplied by (precipitation) the PRISM climate normals. The downscaled climate data were then interpolated to a 1-km resolution. Our analysis used projections from the two best-performing global circulation models (GCMs) for Alaska (Walsh et al. 2008), under three emission scenarios (i.e., low [B1], moderate [A1B], high [A2]) from the Intergovernmental Panel on Climate Change's (IPCC's) Special Report on Emission Scenarios (SRES; Nakićenović and Swart 2000), which bound the climate scenarios from most warming (ECHAM) to least warming (CCCMA) trends. The delta method was implemented by calculating climate anomalies applied as differences in temperature between seasonal future Coupled Model Intercomparison Project (CMIP3; Meehl et al. 2007) data and calculated CRU climate normals for 1961–1990 for four seasons, including winter (December–February), spring (March–May), summer (June–August), and fall (September–November) (data *available online*).[14] Growing season length was computed as the number of days between the day of thaw and day of freeze. The days of thaw and freeze are assigned as the day when the monthly temperature crosses zero degrees Celsius (assuming a linear trend between monthly midpoint temperatures). Similarly, solar radiation and humidity/vapor pressure were derived as input fields for DOS-TEM (Rupp et al. 2016). Additional methodological details for all the downscaled climate variables can be found in the individual metadata files at the Scenarios Network for Alaska and Arctic Planning (SNAP) data download website (see footnote 14). Data associated with this paper are available through multiple sources. Readers are referred to Appendix S1: Table S1 for a breakdown of the data sets and the sources of data sets used in this manuscript.

Distribution of uplands, wetlands, and surface waters

Wetland and upland ecosystems in Alaska were characterized by upscaling a random subset of National Wetlands Inventory (NWI; data *available online*).[15] interpretations using a boosted decision tree model and remote sensing data (He et al. 2016). Model training and test data consisted of wetland and non-wetland designations from the NWI data set, which are based on the classification system of Cowardin et al. (1979) and interpreted from aerial photography. Here, we focused on

[13] http://www.prism.oregonstate.edu
[14] http://www.snap.uaf.edu
[15] http://www.fws.gov/wetlands/Data/State-Downloads.html

developing a thematic map of specific wetland types (i.e., bogs and fens) with distinct water regimes and vegetation cover. Bogs were defined as areas that were generally saturated with shrub and scrub cover, which correspond to areas with NWI codes SS4B, SS1E, and SS7B. Fens are generally flooded throughout the growing season and typically have persistent emergent wetland vegetation. Therefore, NWI codes EM1F and EM1E were used to define areas with fens. All other land cover types where grouped into one class and correspond to areas with neither bogs nor fens in the NWI data set. Together, the distributions of bogs and fens define the extent of wetlands in Alaska, which was needed by the DOS-TEM and the methane dynamics module of the TEM (MDM; Zhuang et al. 2004, He et al. 2016) to simulate CO_2 and CH_4 exchange, respectively, of Alaska wetlands with the atmosphere.

After model calibration, which consisted of developing a parsimonious model with little difference between training and 20-fold cross validation accuracies, the model was applied to geospatial inputs to create a thematic map of bog, fen, and non-wetland land cover classes. Topographic metrics (i.e., elevation and slope) derived from a digital elevation model (DEM; Gesch et al. 2002) served as the primary input for upland and wetland mapping delineations. Accuracy assessments of the resulting 30-m spatial resolution, Alaska Land Carbon Wetland Distribution Map (ALCWDM) were made using independent wetland interpretations (n = 1,030). After accuracy assessments were conducted, the thematic ALCWDM map was resampled to 1-km resolution for modeling purposes, where the number of bog and fen 30-m pixels were used to calculate the percentage frequencies of the two wetland types within each 1-km pixel.

Contemporary estimates of surface water distribution were made separately, developed from the National Hydrography Database (NHD; *available online*),[16] and used within studies of aquatic carbon fluxes from inland waters (Stackpoole et al. 2016). NHD data were compiled to meet the National Map Accuracy standards and qualitatively evaluated by experts. The surface water polygons (i.e., reservoirs, lakes, ponds) were then rasterized to represent surface water extents in the State.

Permafrost distribution and active-layer thickness

Historical permafrost distribution and active-layer thickness.—New and existing maps of near-surface (within 1 m) permafrost (NSP) and active-layer thickness (ALT) were developed and compiled for this assessment (Table 1). New characterization efforts upscaled field observations using remotely sensed or derived data sets. Permafrost observations used in the creation of new maps were unevenly spaced because of cost and logistical issues associated with sampling in remote areas, and thus, do not reflect a systematic or random sample of Alaska's ecotypes. Each of the new maps made used similar input spatial data sets and field observations with variations among products. For instance, the STATSGO product made use of Natural Resources Conservation Service (NRCS) pedons and the General Soil Map of Alaska (Soil Survey Staff 2012, Wylie et al. 2016), while the USGS's Biological Sequestration Assessment (LandCarbon) product made use of additional field observations, topographical data, land cover information, and other remotely sensed and derived data sets (Pastick et al. 2015*a*). In addition to varying field observation and spatial inputs, new data products made use of different scaling methodologies. For example, the LandCarbon products made use of an ensemble of decision tree models and geospatial data to upscale field observations, while the STATSGO products applied observation means to thematic land surface data. Subsequently, these spatial data sets are independent of one another, with much of the (unquantifiable) map variation occurring from different scaling approaches.

Table 1. Summary of spatial and process model near-surface (within 1 m) permafrost (NSP) and active-layer thickness (ALT) data products evaluated.

Source	Resolution	Method	References
LandCarbon	30 m	data mining	Pastick et al. (2015*b*)
STATSGO	1 km	means extrapolated to polygons	Wylie et al. (2016)
GIPL[1.3]	2 km	numerical model	Marchenko et al. (2008)
DOS-TEM	1 km	process-based model	Wylie et al. (2016)

Note: The LandCarbon, STATSGO, and DOS-TEM products are new map products developed for this assessment.

Permafrost maps from the empirical and numerical models were used to independently assess historical (2000–2009) outputs (1-km resolution) from DOS-TEM, which is informative for assessing how well processes related to the spatial distribution of permafrost properties were represented in this biogeochemical, process-based model. Comparisons were made at scales ranging from the entire study domain to finer ecotype units (i.e., upland and lowland land cover types stratified by Landscape Conservation Cooperatives and Level II Ecoregions [Nowacki et al. 2003]). This geographic framework of four Landscape Conservation Cooperative (LCC) Regions (i.e., Arctic, Western Alaska, Northern Interior Forest, and Southern Interior Forest) allows scientific findings to be relevant to land-use managers and stakeholders, and readers are referred to McGuire et al. (2016) for a broad overview of ecological characteristics in each of the LCC Regions. DOS-TEM estimates were compared to map products using a mean product estimate (i.e., product mean excluding DOS-TEM) and the range of product mean estimates. Non-vegetated areas were excluded from comparisons because of the lack of long-

[16] http://nhd.usgs.gov/

term monitoring sites needed to simulate permafrost extent and ALT by DOS-TEM. Permafrost comparisons were not made for ecotypes outside of permafrost zones (i.e., North Pacific LCC), and areas estimated to have ALT >1 m were given a value of 101 cm for a direct comparison between maps with different depth of investigations. Due to the variable original mapping scale (e.g., 30 m, 1:1 000 000) and mapping approaches (e.g., raster mapping and photo interpreted polygons) of the various products, grid cell product comparisons were avoided. Multi-product comparisons reduce consequences of errors (i.e., commission and omission) that are more likely to occur when only one reference product is used.

Projections of permafrost distribution and active-layer thickness.—We used DOS-TEM to estimate changes in ALT, NSP, and deep (within 5 m of the ground surface) permafrost extent from 2010 to 2100 in response to projections of climate and wildland fire. In this process-based model, permafrost extent and ALT are assessed based on soil temperature and soil moisture simulations over an approximately 56 m deep soil column (Yi et al. 2010). Soil temperature and soil moisture in DOS-TEM are driven by climate, soil texture, and drainage conditions. Soil moisture is impacted by water uptake from vegetation and runoff. The insulating properties of snow, moss, and organic layers are also accounted for in the model (Genet et al. 2013). A two-directional Stefan algorithm is used to predict the positions of freezing/thawing fronts in the soil. An evaluation of the performance of the soil temperature and moisture simulations by DOS-TEM has been conducted in burned and unburned forest and Arctic tundra sites in Alaska (Yi et al. 2009). Climate forcing data are described in *Downscaled climate variables.* Soil texture and drainage information was prescribed using the Global Gridded Surfaces of Selected Soil Characteristics (Global Soil Data Task Group 2000) and a DEM (Gesch et al. 2002). For a more detailed description of the model and the forcing data used for the simulations, readers are referred to Genet et al. (2016). Permafrost extent and ALT projections were estimated by averaging annual estimates for two time periods (i.e., 2050–2059 and 2090–2099). DOS-TEM estimates of future NSP extent were also compared to statewide projections made by the Geophysical Institute Permafrost Laboratory (GIPL) model (version 1.3; Marchenko et al. 2008) and those made for the LandCarbon assessment (Pastick et al. 2015*a*), both of which assumed static biophysical conditions and were solely forced by future climate projections. Comparisons of deep permafrost extent are not given because of differences in the depth of investigation.

Fire disturbance and vegetation dynamics

We used a state and transition simulation model, the Alaska Frame-based Ecosystem Code (ALFRESCO; Rupp et al. 2000), to simulate future changes in vegetation dynamics and fire regime in response to different climate model/emission scenarios. ALFRESCO is a spatially explicit, stochastic landscape succession model for Arctic, sub-Arctic, and boreal vegetation types that operates at 1-km resolution and an annual time step. The model represents seven general vegetation types (shrub tundra, graminoid tundra, wetland tundra, white spruce forest, black spruce forest, early-successional deciduous forest, and coastal temperate forest). The baseline land cover types for the assessment domain and models, generated on the North American Land Change Monitoring System (NALCMS) land cover map from 2005, consisted of early succession deciduous vegetation (30%), followed by white spruce forest (9%), black spruce forest (6%), and temperate rainforest (6%). Tundra cover was dominated by shrub tundra (17%), followed by graminoid tundra (10%), and wetland tundra (1%). Currently, the coastal temperate forest type and the wetland tundra type are represented as static vegetation states in ALFRESCO, since there is no strong evidence for transitions occurring from these vegetation states to a different state (e.g., wetland tundra does not transition to shrub tundra).

The fire module of ALFRESCO uses a cellular automata approach with separate subroutines for cell ignition and spread to simulate annual fire season activity. Both ignition and fire spread (i.e., flammability) are a function of growing season climate (Duffy et al. 2005), vegetation type, and time since last fire. The ignition of any given cell is stochastic in nature and determined by comparing a randomly generated number against the flammability coefficient of that cell. The flammability coefficient allows for changes in flammability that occur through succession (i.e., fuel build up). Following a wildfire in ALFRESCO, general successional trajectories for forested systems were as follows: burned spruce forest (white or black) transitioned into early-successional deciduous forest, and burned deciduous forest self replaces.

Vegetation transition times differed probabilistically between climax black and white spruce trajectories (Rupp et al. 2002). Transitional times were modeled probabilistically to represent early-successional (i.e., recolonization) deciduous vegetation following wildfires in spruce and deciduous forest and to determine the amount of time, in the absence of fire, until the climax spruce stage dominates the site again. Self-replacement of deciduous forest can occur when repeated burning and/or climate conditions preclude transition to climax spruce. ALFRESCO incorporates the effects of fire severity on transition times using measurements of the area of the wildfire (i.e., fire size), complex topography, and vegetation type on flat landscapes (Duffy et al. 2007, Johnstone et al. 2011).

Transitions in tundra are driven by succession or colonization and infilling. These processes are influenced by climate and fire history, which affect seedling establishment and growth conditions and proximity to seed source. For the transition from tundra to forest at treeline, seed dispersal occurs within a 1-km neighborhood.

White spruce colonization/infilling is possible in both graminoid and shrub tundra with transition rates to spruce forest mediated by effects of warming climate conditions and corresponding basal area growth accrual. Vegetation succession from graminoid to shrub tundra is modeled probabilistically, with a greater likelihood of transition to shrub tundra post-fire. In the case of wildfire activity, shrub tundra transitions to graminoid tundra and graminoid tundra self replaces.

We calibrated the relationship between climate and fire by comparing model output (e.g., fire regime, stand age structure) to the corresponding historical data (Mann et al. 2012). Analysis and synthesis of historical fire activity (1950–2015) were based on estimates from fire management records maintained by the Alaska Interagency Coordination Center (data *available online*).[17] This database includes digitized fire perimeters, which were used to generate summary statistics across the simulation domain. Simulated vegetation and fire dynamics were analyzed and synthesized across the full ensemble of simulations (n = 200) and for all three emission scenarios of the two GCMs used in this analysis.

Results

Climate trends

Temperature and growing season length.—Mean annual air temperatures have increased 1.7°C from 1950 to 2013 in Alaska. Mean winter temperatures have increased the most (3.1°C) followed by spring (1.6°C), summer (1.1°C), and fall (0.9°C). Growing season lengths have also increased across Alaska, and these increases are primarily due to an increase of average maximum temperatures during May–June, which generally corresponds to the start of the growing season throughout much of Alaska. Projected future climate scenarios suggest that general warming trends will continue through this century. Appendix S1: Fig. S1 shows maps and boxplots of the projected temperature change for the A1B ECHAM and CCCMA model output for the period 2090–2099 minus the average of the historical period 1950–2013. Increases in temperature that were mediated by either season or timing within the period 1950–2013 were averaged for the sake of this comparison to the 2090–2099 decade. The box plots indicate that the temperature deltas for the ECHAM model are substantially larger than those for the CCCMA model. For each of the seasons, the 25th percentile of the ECHAM model temperature departures is above the 75th percentile of the CCCMA model temperature departures. Warming is projected to occur across both models and emission scenarios with the minimum median seasonal increase of approximately 1.5°C occurring in the spring for the CCCMA model and the maximum median increase of approximately 5.6°C occurring in the fall for the ECHAM model. Seasonal differences in the magnitude of warming are projected to persist with the greatest increase occurring in winter and fall and in northern and western Alaska (Appendix S1: Fig. S1). Projected changes in climate can be translated into projected estimates of growing season length. For both the CCCMA and the ECHAM models, the length of the growing season is projected to get longer, with the largest increases occurring in northern and western Alaska (Appendix S1: Fig. S2).

[17] https://fire.ak.blm.gov/

Distribution of upland, wetland, and surface water.—Mapping results indicate that wetlands and uplands respectively cover 177 069 and 1 237 775 km^2 or 12.5% and 87.5% of the total land surface area (including inland water) of Alaska (Fig. 2). Surface area of inland waters was ~60 000 km^2, using the modified NHD data set, which represents nearly 3.5% of the total area of mainland Alaska. Overall accuracy of the thematic ALCWDM map and model ranged from 67% to 75% using independent interpretations and 20-fold cross validations. Average producer accuracies for bogs, fens, and other land cover types were approximately 44%, 56%, and 85%, respectively. Average user accuracies for bogs, fens, and other land cover types were 54%, 79%, and 72%, respectively. No accuracy results are presented for the modified NHD data set because of the lack of independent observations of surface water extent for the State.

Permafrost distribution and active-layer thickness

Historical permafrost distribution and active-layer thickness.—Near-surface (within 1 m) permafrost was estimated to underlie 36–61% of mainland Alaska, and NSP extent simulated by DOS-TEM was outside this range at 22%. DOS-TEM estimates were generally lower than mean NSP abundance/extent estimates (excluding DOS-TEM estimates, Fig. 3), falling outside the range of estimates for 70% of major ecotypes. Likewise, DOS-TEM ALT estimates were generally higher than the mean ALT for each ecotype, falling outside the range of estimates for 73% of major ecotypes. DOS-TEM estimated frequency and ALT were generally in good agreement with empirical and numerical estimates in arctic tundra. However, DOS-TEM estimates of NSP frequency and ALT were lower and higher, respectively, than the product means and ranges in both Northern Interior Forest and Western Alaska.

Projections of permafrost distribution and active-layer thickness.—DOS-TEM permafrost simulations suggest that near-surface permafrost will underlie 10–20% of the terrestrial landscape by the end of the 21st century under both GCMs and all three SRES (Table 2). This 9–55% estimated loss of NSP extent, compared to the historical period (2000–2009), takes future change in climate and fire regime into account and is generally smaller than the range of estimates (i.e., 53–74%) made by models

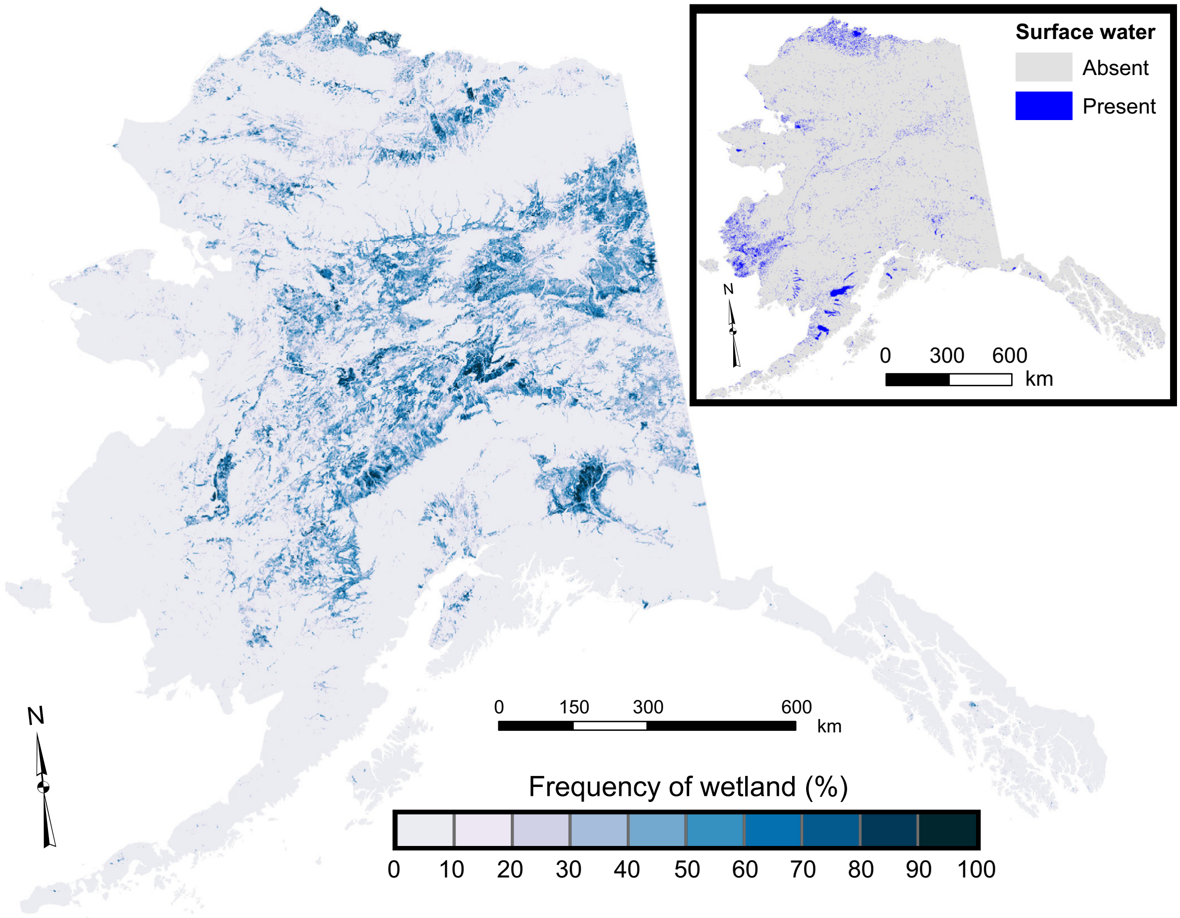

FIG. 2. Historical estimates (1 × 1 km spatial resolution) of the percentage cover of wetlands (i.e., bog, fen) and (inset) surface water bodies in Alaska.

that solely account for changes in climate. However, the DOS-TEM baseline estimate of NSP extent is smaller than other model estimates, and thus there is less NSP to be lost in the future. Model results indicate that NSP loss will be most pronounced for Interior and Western Alaska, and the majority of models indicate that NSP is likely to persist on much of the North Slope by the end of the 21st century (Appendix S1: Fig. S3).

In contrast to projections of NSP (within 1 m) loss, DOS-TEM simulations suggest that deep (within 5 m of the ground surface) permafrost will remain on 19–34% of Alaska by the end of the 21st century (Fig. 4). For areas where permafrost is present within 5 m of the ground surface, DOS-TEM estimated ALT to be 1.3 m, 1.4–2.1 m, and 0.7–1.8 m for 2000–2009, 2050–2059, and 2090–2099, respectively. While the notion of overall shallowing of the active layer is not intuitive, this occurs because the areas where the top of the permafrost is deeper than 5 m (ALT >5 m) do not contribute to these estimates. In the mid- and late-century estimates, the permafrost with deeper ALT within the last decade tends to be lost and the residual area of permafrost had shallower ALT. Increases in deep permafrost thaw and active-layer depth are greater under CCCMA scenarios than that of the ECHAM scenarios at the midpoint of the 21st century. After 2050–2059, results indicate permafrost loss and active-layer thickening will generally be greater under ECHAM climate projections. As was the case with NSP, deep permafrost is most likely to be lost in Interior and Western Alaska.

Fire disturbance and vegetation dynamics

Historical fire disturbance.—Wildfire activity has increased in terms of both frequency and extent of large fire years throughout the period 1950–2015 (Fig. 5). Since 2000, an annual average of 678 595 ha was burned, more than twice the annual average of 333 216 ha for the period 1950–1999. Historical model simulations and the observed fire perimeter data compare well with annual area burned averaging 378 900 and 379 100 ha, respectively. Historical observations of the inter-annual variability of area burned was high, with slightly smaller inter-annual variability simulated by ALFRESCO, and

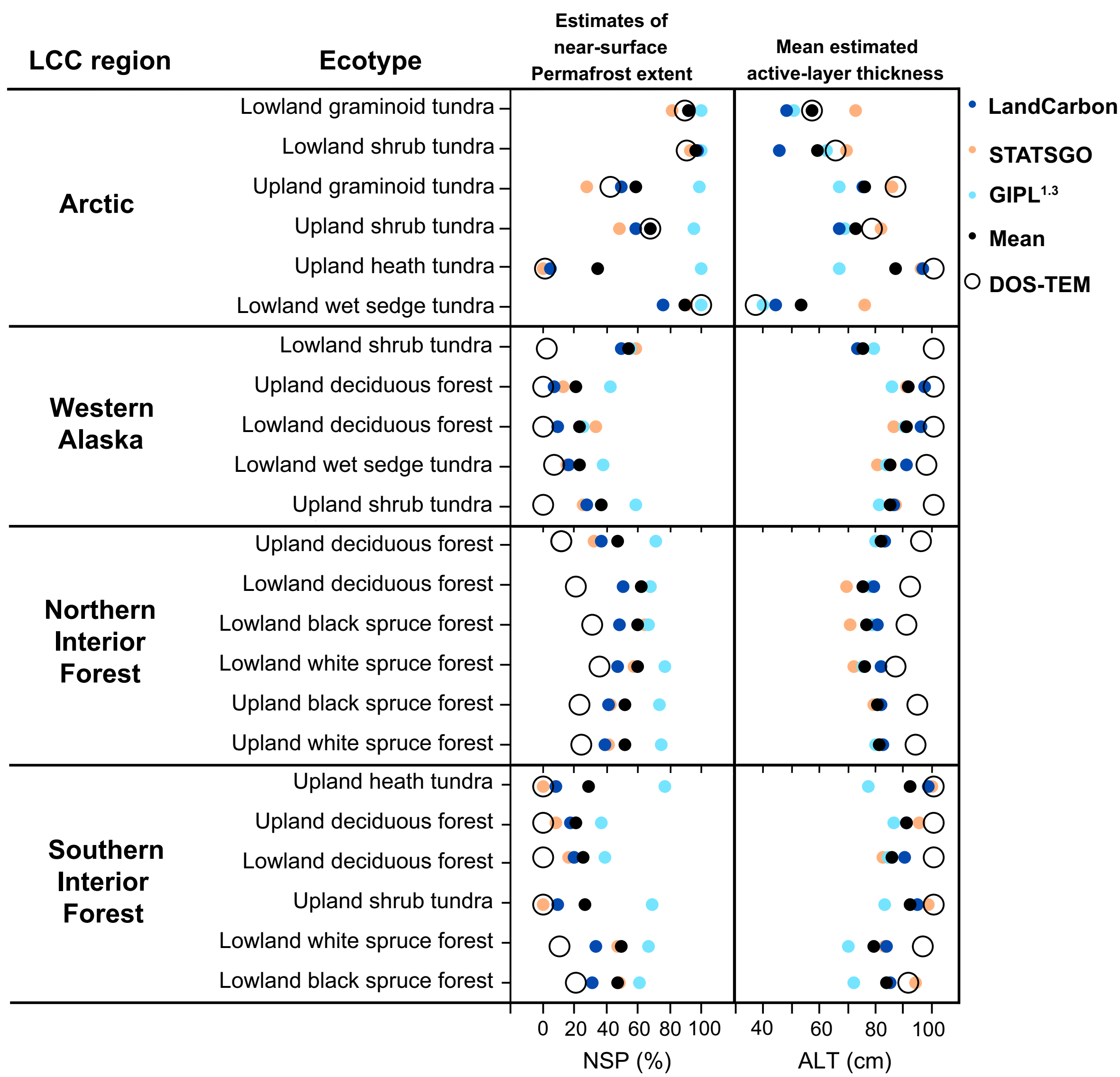

FIG. 3. Extent of near-surface (within 1 m) permafrost (NSP) and averaged active-layer thickness (ALT) of major ecotypes in each Landscape Conservation Cooperative (LCC) Region. Areas estimated to have ALTs >1 m were given a value of 101 cm for direct comparison and to account for differences in investigation depths.

TABLE 2. Estimates of near-surface (within 1 m) permafrost extent in Alaska during the 21st century, as made by the Geophysical Institute Permafrost Laboratory (GIPL) model (version 1.3; Marchenko et al. 2008), the LandCarbon assessment (Pastick et al. 2015*b*), and the dynamic organic soil version of the Terrestrial Ecosystem Model (DOS-TEM).

	Near-surface (within 1 m) permafrost extent			
Model	2000–2009	2050–2059	2090–2099	Emission scenario
GIPL[1.3]	61%	39%	21%	A1B
LandCarbon	38%	20–27%	10–18%	B1, A1B, A2
DOS-TEM	22%	14–21%	10–20%	B1, A1B, A2

Note: A range of estimates is given for models that made use of multiple emission scenarios (i.e., B1, A1B, and A2), and results from A1B emission scenario are mapped in Appendix S1: Fig. S3.

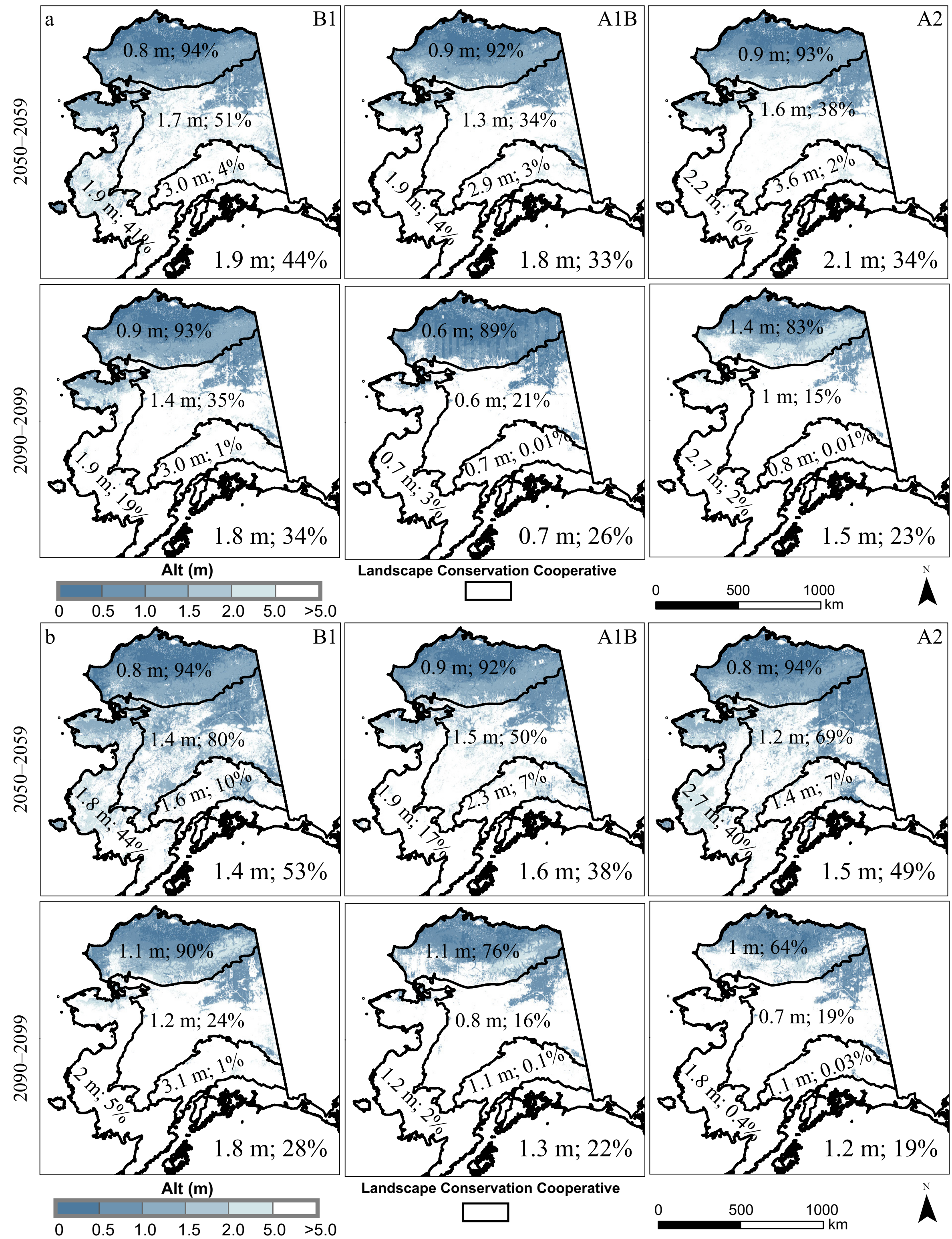

FIG. 4. DOS-TEM projections of active-layer thickness (ALT) for each climate model (a) CCCMA, (b) ECHAM, and all three emission scenarios (B1, A1B, A2) for two time periods (i.e., 2050–2059 and 2090–2099). Areas in white correspond to estimates of no permafrost within 5 m of the ground surface. Mean ALT and percentage area of deep (within 5 m of the ground surface) permafrost are given for each Land Conservation Cooperative (LCC) region we analyzed (i.e., Arctic, Northern Interior, Southern Interior, and Western Alaska) and all of Alaska (excluding the North Pacific LCC).

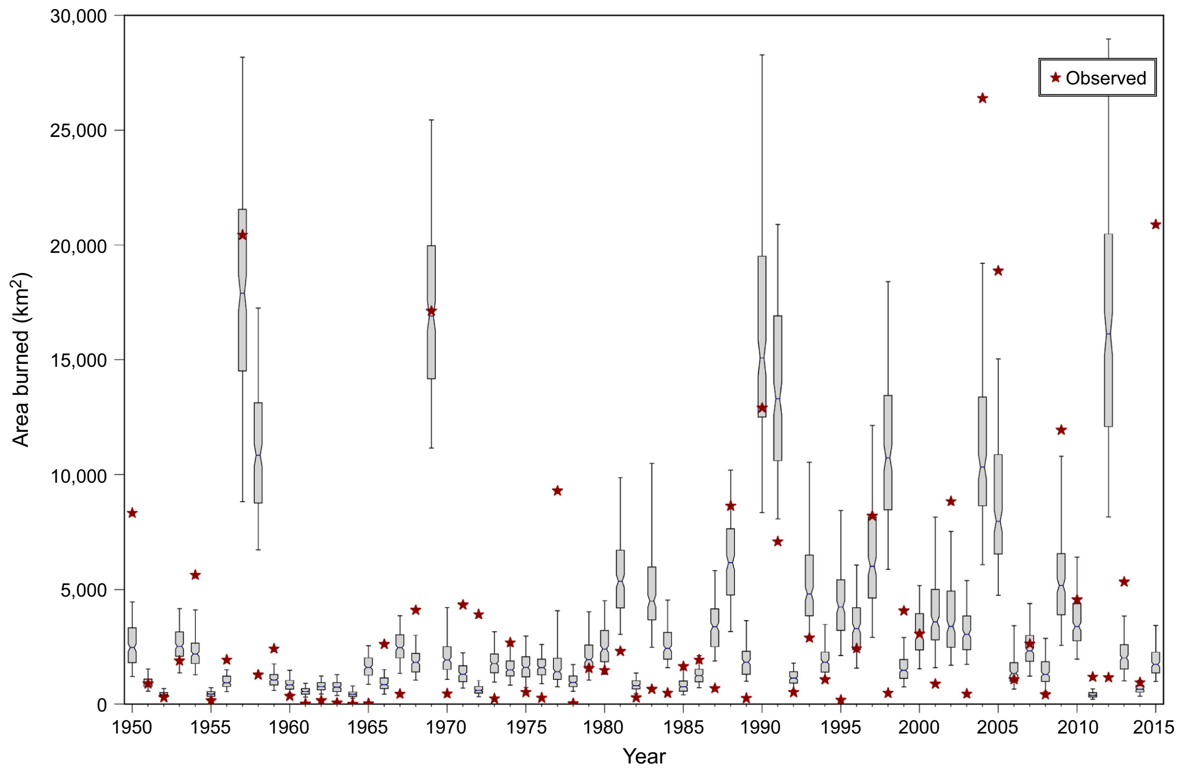

Fig. 5. Historical annual area (ha) burned in Alaska (1950–2015). Sources: Gabriel and Tande (1983), Todd and Jewkes (2006), Alaska Department of Natural Resources, and the Alaska Fire Service, Bureau of Land Management. Violin plots show the distribution of simulated annual area burned output across 200 replicates from the Alaska Frame-based Ecosystem Code (ALFRESCO). [Color figure can be viewed at wileyonlinelibrary.com]

approximately 85% of fires occurred in the interior boreal region of Alaska. Overall, ALFRESCO reliably replicated the probability distribution of historical fire sizes, historical annual burned area and inter-annual variability, and fire extent across the landscape.

Projections of fire disturbance and vegetation dynamics.— ALFRESCO projections presented here made use of the A1B scenario and indicate increases in statistical measures of wildfire activity across both climate models over the next century (Fig. 6). The median projected annual area burned for the CCCMA and ECHAM models was 207 300 and 273 000 ha, respectively. These are large increases relative to the median from the historical period of 159 600 ha. With respect to the mean, projected annual area burned was 379 300 and 549 100 ha, respectively. Hence, there is no meaningful change in the mean for the CCCMA model relative to the historical period mean of 379 100 ha and a substantial increase in the mean for the ECHAM model. Inter-annual variability is projected to be higher in the ECHAM scenarios relative to the CCCMA. As a corollary, ECHAM projections also include a greater number of extreme annual area burned events. The timing and magnitude of increased fire activity differs between GCMs. The CCCMA model shows the greatest increase in fire activity in the middle and second half of the next century, while the ECHAM model shows a relatively consistent and more pronounced increase in fire activity.

ALFRESCO simulations project that spruce forest will decrease by 8% under the CCCMA model and 38% under the ECHAM model across the full assessment domain by 2100 (Fig. 7). In addition the projections suggest, deciduous forest will increase by 15% under the CCCMA model and 52% under the ECHAM model (Fig. 7). In Northern Interior Alaska, spruce forests are projected to decrease by 8% under the CCCMA model and 44% under the ECHAM model, and deciduous forest are projected to increase by 25% under the CCCMA model and 113% under the ECHAM model. The transformation of late-successional spruce forest to early-successional deciduous trees is mainly due to increased wildfire activity in interior Alaska. Under the ECHAM model, shrub tundra is projected to increase by 8% and graminoid to decrease by 26% by 2100 (Fig. 7). These projections contrast estimates under the CCCMA model, where shrub and graminoid tundra are projected to decrease as much as 3% and 15%, respectively (Fig. 7). When examining changes to land cover in the Arctic LCC, which are largely driven by climate rather than fire activity, graminoid tundra is projected to decrease by 10% under the CCCMA model and 24%

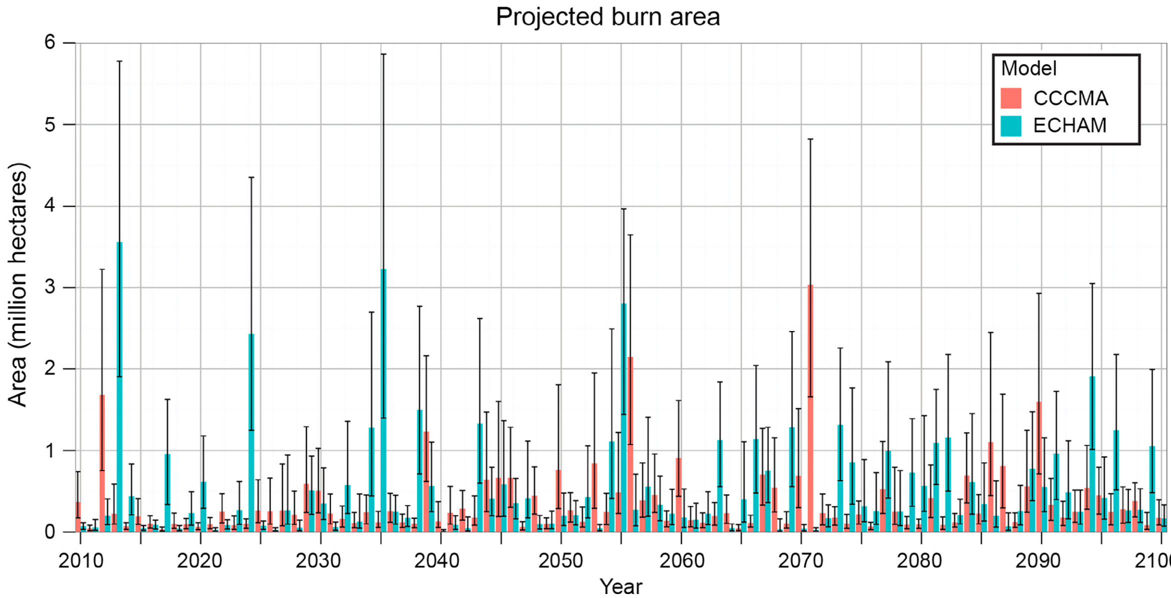

Fig. 6. Projected annual area (ha) burned across Alaska from 2010 to 2100 for CCCMA (red bars) and ECHAM (blue bars) for the A1B emission scenario. Error bars represent 95% confidence intervals constructed from individual simulations (n = 200).

under the ECHAM model, and shrub tundra is projected to increase by 4% under the CCCMA model and 21% under the ECHAM model. The largest relative increase in deciduous forest cover are expected in the Arctic LCC, with projected increases of 233% and 620% under the CCCMA and ECHAM models, respectively.

Discussion

The goal of this study was to analyze the historical and projected distribution of environmental factors that drive ecosystem carbon dynamics in Alaska by using an array of modeling and statistical techniques to estimate historical and future climatic variables, wetland, upland, and surface water distribution, permafrost extent and active-layer thickness, and fire and vegetation dynamics in Alaska (Fig. 1). In the following sections, we discuss (1) our results in relation to ecosystem carbon dynamics and previous research, (2) limitations of our approach, and (3) possible avenues for improvements.

Climate trends

Alaska's average annual statewide temperatures have increased by 1.6°C over the past six decades (Stewart et al. 2013), which is generally consistent with the historical downscaled temperature data used in this study. This warming is not uniform across the state and is not consistent across seasons. The greatest observed temperature increases have occurred during winter and spring (Hinzman et al. 2005), two to three times the level of warming found in summer and fall. Regionally, the interior continental portions of the state have experienced the most warming with some areas rising more than 4°C, whereas coastal and maritime areas have experienced change on the order of 0.5–1.0°C (Shulski and Wendler 2007). These recent climate trends have a major effect on carbon dynamics in Alaska both directly via changes in biogeochemical processes (Fig. 1(2)) as well as indirectly through the impacts of substantial changes in vegetation characteristics (Fig. 1(8)) and increases in disturbance (e.g., wildfire, permafrost degradation) extent, frequency, and severity (Fig. 1(5 and 9)).

Mean annual air temperatures in Alaska are estimated to further increase by 1.8° to 4.8°C by the end of the 21st century. The largest departures in mean annual temperature occurred for winter and fall seasons in northern and western Alaska, which coincides with historical observations of greater warming in the winter season (Serreze et al. 2000). Large increases in winter temperatures may increase active-layer depth in Arctic regions (Fig. 1(4)), which would stimulate cold-season methane emissions from vast stores of labile organic matter and would serve as a positive feedback to climate warming (Zona et al. 2016). Under expected future warming, the rate of carbon uptake of Alaska's ecosystems could increase, however, because of the sensitivity of vegetation productivity to temperature (Fig. 1(2)). Note that, while precipitation is generally forecasted to increase, there is both lower magnitude and more uncertainty among seasons and GCMs, as compared to temperature projections, and a thorough analysis of GCM forecasts of precipitations was beyond the scope of this work.

The sparse network of weather stations in Alaska contribute to uncertainties in estimating historical climate variables. While the current configuration of weather

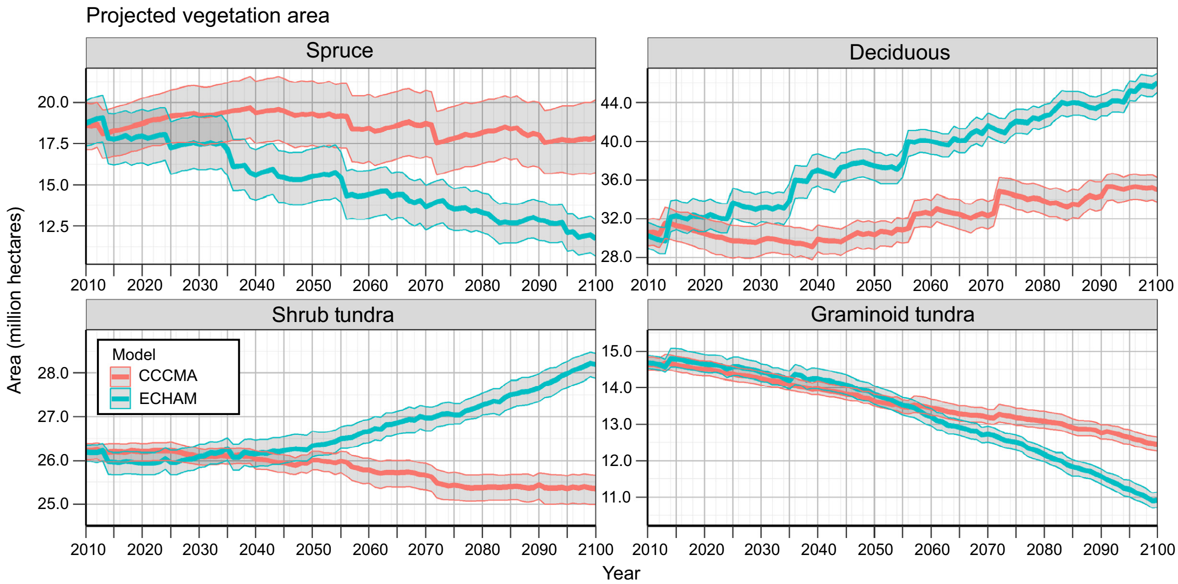

FIG. 7. Projected (2010–2099) areal extent (ha) of major forest and tundra vegetation types for the CCCMA (red) and the ECHAM (blue) under the A1B emission scenario. Gray-shaded area shows 95% confidence intervals constructed from individual simulations (n = 200).

stations can lead to fair estimates of regional temperatures, the accurate quantification of more heterogeneous climatic variables (i.e., precipitation) remains problematic (Walsh et al. 2008) and topographical data used for downscaling are relatively poor. Improved estimates of historical climates could thus be made through the strategic placement of additional weather stations and by improving dynamic-downscaling techniques.

Another important source of uncertainty associated with our results is the depiction of future climate change by GCM-based scenarios. Part of this uncertainty is driven by the structure of the GCMs and separate portion is driven by the emission scenarios. Uncertainty associated with the emission scenarios is based on a number of assumptions about the behavior of future society, as well as the potential feedbacks within the carbon cycle system (e.g., permafrost carbon feedback, vegetation feedback), which are poorly constrained (Koven et al. 2015). We provide bounds for uncertainty associated with GCM-based projections by using coupled, global GCM-SRES scenarios that best span the range of variability for the region (Walsh et al. 2008). Future efforts should consider using Coupled Model Intercomparison Project Phase 5 (CMIP5) model outputs from the IPCC's Fifth Assessment Report (AR5) that may provide more accurate climate forecasts.

Distribution of uplands, wetlands, and surface waters

Wetlands play a fundamental role in the carbon cycle and in regulating climate because of their ability to sequester large amounts of carbon and to act as a potential source of greenhouse gases. Despite the sensitivity of wetlands and their carbon stocks to climatic change, little has been done to quantify their historical distribution across large areas and in great detail, which is a fundamental step in understanding future change and regional carbon stocks and fluxes (Fig. 1(3)). Our mapping results represent a novel approach to quantify specific wetland types (i.e., bogs and fens) throughout Alaska, and the ALCWDM product is useful for partitioning environmental variability according to drainage conditions and dominate biogeochemical pathways of carbon release.

Our estimate of wetland extent is smaller than those made by Whitcomb et al. (2009) and Clewley et al. (2015) who combined NWI interpretations, synthetic aperture radar imagery, topographic metrics, and other spatial data into a decision-tree modeling framework to quantify the distribution of all wetland types and upland land covers in Alaska. Estimates of the proportion of non-wetland extent ranged from 59–76% in those studies (when clipped to our study area), which are less than the 87.5% estimated in this study. Discrepancies between estimates of areal extent of wetland distribution are primarily caused by variations in the specific wetland types mapped, where previous assessments tended to delineate a larger number of lowland-permafrost plateaus as wetlands. Likewise, differences in modeling approaches (e.g., random forest vs. boosted decision tree models) and remote sensing inputs likely account for a portion of the discrepancies between studies.

Accurate quantification of the distribution of bogs and fens remains difficult because land surface features (e.g., vegetation, topography), as represented by remote-sensing imagery or derived products, are not always good indicators of wetland types primarily differentiated by hydrological connectivity and inputs. Moreover, bogs and fens naturally occur in close proximity to one another, where fens and bogs can transition between one another due to succession, paludification or infilling, and changing hydrologic regimes, therefore distinguishing between them using moderate resolution imagery is challenging. However, accuracy assessments indicate that the ALCWDM map is fairly consistent with NWI interpretations of vegetation characteristics and water regimes, and thus suitable for use within regional studies of carbon stocks and fluxes. Because the robustness of carbon balance estimates largely depends on the accuracy of the wetland distribution maps, additional field data, more recent and accurate manual interpretations of wetland types, and improved methods are needed to better quantify wetland types and distribution throughout Alaska.

In comparison to wetlands, surface water extents are easier to quantify because of strong relations between the spectral signature of open water and data captured by remote-sensing sensors. However, the NHD data used in this study were developed from a coarse (1:63 360) topographic map and therefore small water bodies and streams were not adequately resolved. Furthermore, variations in surface water and wetland extent were not quantified in this assessment, so these fluctuations were not accounted for in models estimating carbon fluxes in this invited feature. As more precise and accurate topographical, wetland, and surface water data become available, they should be incorporated into regional analyses of terrestrial and aquatic carbon fluxes.

Permafrost distribution and active-layer thickness

Permafrost temperatures in Alaska have risen in correlation with mean annual air temperatures (Romanovsky et al. 2010), but thickening of the active layer is less frequently documented because of soil subsidence over time (Streletskiy et al. 2013, 2016). While these observations serve as a signal for local changes in permafrost properties, there is a need to move beyond the sparse, point measurements to understand change at regional scales. One approach to better understand permafrost systems is by means of empirical, numerical, and process-based modeling, as shown in this study. Furthermore, by comparing multiple model outputs, we reveal uncertainties related to our current understanding of the distribution of permafrost and ALT, as well as provide strong evidence that permafrost in Alaska is prone to further perturbation.

Intra-permafrost product comparisons made in this study indicate large uncertainties related to the understanding of the current distribution of NSP and ALT in Alaska. Uncertainties associated with how permafrost characteristics are measured in the field, temporal variability among permafrost observations, and inherent difficulties in assessing thaw depths in dry-rocky soils can influence empirical mapping results and thus our comparative analyses. For example, the analysis of NSP by the LandCarbon assessment, which is limited to 1-m depth because few field data extend beyond this depth, estimates substantially less NSP than the GIPL model due in part to large differences in how the models deal with high-elevation rocky soils. Indeed the largest differences between empirical and numerical model simulations of NSP extent were consistently within upland ecotypes more likely to be underlain with rocky soils. Another source of uncertainty is the lack of high quality and spatially detailed surficial deposit and soil texture information for the entire State which is needed to accurately calibrate numerical and process-based models (Jafarov et al. 2012).

The effect of fire disturbances on soil thermal and hydrological regimes may also be responsible for differences in model estimates for Interior and Western Alaska. For example, the largest difference in estimates for the boreal region were between DOS-TEM and the GIPL model, where DOS-TEM accounts for the effect of fire on the organic layer and the consequences on the soil thermal and hydrological regimes and the GIPL model does not. The inclusion of remote sensing information into process models has remained limited, but has potential for improving historical simulations of permafrost distribution and response to disturbance (National Research Council 2014, Zhang et al. 2014). Likewise, empirical models that incorporate remote sensing information have been shown to estimate post-fire permafrost conditions with high fidelity (Minsley et al. 2016). However, the explicit quantification of deep permafrost properties by empirical models remains problematic because of difficulties in observing deep permafrost conditions and potential disconnects between surface and subsurface properties. While the effects of fire-induced change on permafrost have been well documented and modeled (Genet et al. 2013, Jafarov et al. 2013, Brown et al. 2015), additional data are needed to better parametrize and validate models estimating permafrost response to abrupt change across a gradient of environmental conditions and disturbance regimes.

While there is disagreement among models as to the current distribution of permafrost and ALT in Alaska, all models agree that the permafrost system will undergo substantial loss in the 21st century. This top-down thawing of permafrost may result in drier or wetter landscape conditions, depending on local factors such as ground-ice content, which ultimately determines how the carbon cycle will change under warming conditions (Fig. 1(5); Jorgenson et al. 2013, Schuur et al. 2015). For instance, permafrost thaw can result in drier soil conditions in uplands that enhance the susceptibility of these areas to wildland fire and can accelerate carbon loss (Harden et al. 2012). Among the models used for this comparison, DOS-TEM is the only one that accounts for future disturbances related to fire and the potential consequences on permafrost stability (Fig. 1(10)). Attribution analysis of future environmental changes on permafrost stability have shown that wildfire can be responsible for substantial decreases in permafrost stability (Genet et al. 2016). Although disturbances related to thermokarst and water dynamics can also have a large effect on the vulnerability and resilience of permafrost landscapes to change (Jorgenson et al. 2010), current models do not account for these important factors. Limitations with the models, in terms of incorporating these processes, and uncertainties related to the knowledge of the present distribution of permafrost, currently constrain our ability to make precise and more meaningful projections.

Fire disturbance and vegetation dynamics

Recent changes in the fire regime in Alaska have been attributed to climate warming (Duffy et al. 2005, Calef et al. 2015), which have resulted in changes to the composition and productivity of boreal and tundra vegetation (Beck et al. 2011). These changes have strong implications for the ecosystem carbon balance (Fig. 1(8 and 9)) and feedbacks to climate, as well as the sustainability of ecosystem properties (Fig. 1(7 and 10)). Our historical simulations of fire extent and frequency align with historical observations, with the largest absolute differences between modeled and observed annual area burned occurring during extreme fires years in Alaska. Large fire events are particularly important because they strongly influence ecosystem carbon dynamics and processes at regional scales. For instance, in the last decade, there has been a twofold increase in the annual area burned as compared to the previous four decades (Kasischke et al. 2010), which resulted in estimated emissions totaling 177 Tg C (Veraverbeke et al. 2015) and 38–39% of the boreal landscape becoming susceptible to long-term deciduous-dominated or co-dominated succession (Barrett et al. 2011, Pastick et al. 2014).

Future simulations suggest that warming will cause a large change in fire regimes for both GCMs considered, with interior Alaska exhibiting the greatest change in fire frequency relative to historic observations. This finding supports previous studies that have shown that climate warming will further increase forest fire activity across boreal regions of Alaska and western Canada (Flannigan et al. 2000, Balshi et al. 2009, Young et al. 2016). Relative to the historical period, simulation results suggest that the median annual area burned will increase on the order of 1.3–1.7 times during the 21st century in Alaska. This projected increase in annual area burned is substantially less than estimates made by Balshi et al. (2009). Discrepancies between projections of annual area burned are likely the result of differences in the climate forcing data used and previous assessments did not account for vegetation dynamics that can impact future fire regimes (Fig. 1(7)).

Landscape-level transitions of late to early-successional forests are expected to occur, which would serve as a negative feedback to regional climate warming and increasing fire activity because of changes in albedo and reduced flammability (Chapin et al. 2000, Rupp et al. 2000), the latter is consistent with modeled decreases in decadal burned area in Interior Alaska during the end of the 21st century. A concurrent shift from long-term deciduous forest cover may also weaken permafrost stability because deciduous forests typically have high rates of decomposition and mineralization that result in the maintenance of thin surface organic layers (Johnstone et al. 2010, Pastick et al. 2014, 2015b). Thus, interrelations between wildland fires and vegetation dynamics are important because of their strong controls on ecosystem processes and conditions, carbon dynamics, and regional climates.

Divergent estimates in statewide changes in shrub and graminoid tundra underscore the importance of the climate forcing data used when projecting changes in tundra land cover types. Simulations of increased shrub tundra in arctic regions are in general agreement with historical increases in vegetation productivity and shrub expansion inferred from remote-sensing data (Walker et al. 2009, Beck and Goetz 2011). However, numerous complexities and interactions among biophysical drivers of shrub expansion exist (Myers-Smith et al. 2011, Jorgenson et al. 2015), and thus accurately modeling local shifts in plant assemblages is difficult. Furthermore, ALFRESCO simulations are currently carried out at 1-km resolution, which is too coarse to depict local changes of vegetation structure and composition related to fire and climate-induced change. Subsequently, additional research using high-resolution imagery, land cover maps, and dynamic vegetation models are needed to improve and constrain estimates of historical and projected changes in vegetation.

Conclusion

Over the last 60 yr, increased mean annual temperatures, longer growing seasons, and increased fire activity have pushed Alaska's ecosystems toward new states and meaningful changes in both structure and function. Warming trends are projected to continue throughout the 21st century, which will result in landscape-level changes to permafrost distribution, vegetation composition, and fire regimes. These changes would alter critical biophysical and biogeochemical processes, including surface energy fluxes, evapotranspiration, and carbon flux and storage, which will provide feedbacks that impact trends in regional climate.

The results presented in this manuscript point to observational needs required to accurately calibrate and validate models that are essential for understanding ecological changes likely to occur in the face of climate warming. A sparse network of long-term monitoring and field-observation sites across representative ecotypes in Alaska gives rise to a wide range of model predictions and uncertainties in estimates of historical conditions. To improve understanding of the drivers of spatiotemporal patterns of carbon dynamics across arctic and boreal landscapes, standardized data reporting, collection practices, and additional observational networks are needed. Correspondingly, while the models used in this assessment incorporate state of the science methods needed to advance our understanding of ecosystem processes in Alaska, a number of biophysical factors, feedbacks, and uncertainties are coarsely characterized or poorly constrained.

In addition to improved model inputs, validation data sets, and handling of error propagation, refinements to model mechanics are needed. For example, while models of vegetation dynamics driven by climate warming and fire disturbance are able to capture logical transitions and productivity changes that are consistent with historical observations, iterative refinements to models are needed, particularly to capture additional disturbance (e.g., thermokarst, insect) effects that influence these dynamics. Ongoing efforts such as the Department of Energy's Next-Generation Ecosystem Experiment (NGEE) Arctic, the National Aeronautics and Space Administration's Arctic-Boreal Vulnerability Experiment (ABoVE), and the U.S. Geological Survey's Biological Sequestration Assessment (LandCarbon) will help build upon the data sets and advances discussed in this invited feature. Although multiple uncertainties exist, this study of drivers serves as a foundation for the attribution of responses of carbon dynamics to environmental variation and change, and particularly to changes in climate and fire regime.

Acknowledgments

This research was funded by the U.S. Geological Survey (USGS) Land Change Science Program, the USGS Biological Carbon Sequestration Assessment (LandCarbon), and the National Aeronautics and Space Administration's Arctic-Boreal Vulnerability Experiment (ABoVE). Additional support was provided by the Department of Interior Alaska Climate Science Center through Grant/Cooperative Agreement G10AC00588 from the U.S. Geological Survey. A portion of this work was performed under USGS contract G08PC91508. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and thank Jeremy Littell (USGS) and anonymous reviewers for constructive comments that improved this manuscript. We also extend our sincere thanks to Tom Kurkowski for helping with data management and distribution. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Literature Cited

Abbott, B. W., J. B. Jones, S. E. Godsey, J. R. Larouche, and W. B. Bowden. 2015. Patterns and persistence of hydrologic carbon and nutrient export from collapsing upland permafrost. Biogeosciences 12:3725–3740.

Balshi, M. S., A. D. McGuire, P. Duffy, M. Flannigan, D. W. Kicklighter, and J. Melillo. 2009. Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century. Global Change Biology 15:1491–1510.

Balshi, M. S., et al. 2007. The role of historical fire disturbance in the carbon dynamics of the pan-boreal region: a process-based analysis. Journal of Geophysical Research—Biogeosciences 112:G02029.

Baltzer, J. L., T. Veness, L. E. Chasmer, A. E. Sniderhan, and W. L. Quinton. 2014. Forests on thawing permafrost: fragmentation, edge effects, and net forest loss. Global Change Biology 20:824–834.

Barrett, K., A. D. McGuire, E. E. Hoy, and E. S. Kasischke. 2011. Potential shifts in dominant forest cover in interior Alaska driven by variations in fire severity. Ecological Applications 21:2380–2396.

Beck, P. S. A., and S. J. Goetz. 2011. Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: ecological variability and regional differences. Environmental Research Letters 6:045501.

Beck, P. S. A., G. P. Juday, C. Alix, V. A. Barber, S. E. Winslow, E. E. Sousa, P. Heiser, J. D. Herriges, and S. J. Goetz. 2011. Changes in forest productivity across Alaska consistent with biome shift. Ecology Letters 14:373–379.

Brown, D. R. N., M. T. Jorgenson, T. A. Douglas, V. E. Romanovsky, K. Kielland, C. Hiemstra, E. S. Euskirchen, and R. W. Ruess. 2015. Interactive effects of wildfire and climate on permafrost degradation in Alaskan lowland forests. Journal of Geophysical Research—Biogeosciences 120:2015JG003033.

Calef, M. P., A. Varvak, A. D. McGuire, F. S. Chapin, and K. B. Reinhold. 2015. Recent changes in annual area burned in interior Alaska: the impact of fire management. Earth Interactions 19:1–17.

Chapin III, F. S., P. A. Matson, and P. M. Vitousek. 2011. Principles of terrestrial ecosystem ecology. Second edition. Springer, New York, New York, USA.

Chapin III, F. S., M. S. Torn, and M. Tateno. 1996. Principles of ecosystem sustainability. American Naturalist 148:1016–1037.

Chapin III, F. S., et al. 2000. Arctic and boreal ecosystems of western North America as components of the climate system. Global Change Biology 6:211–223.

Chapin III, F. S., et al. 2006. Reconciling carbon-cycle concepts, terminology, and methodology. Ecosystems 9:1041–1050.

Chapin III, F. S., et al. 2010. Resilience of Alaska's boreal forest to climatic change. Canadian Journal of Forest Research 40:1360–1370.

Christensen, T. R., T. Johansson, H. J. Åkerman, M. Mastepanov, N. Malmer, T. Friborg, P. Crill, and B. H. Svensson. 2004. Thawing sub-arctic permafrost: effects on vegetation and methane emissions. Geophysical Research Letters 31: L04501.

Clewley, D., J. Whitcomb, M. Moghaddam, K. McDonald, B. Chapman, and P. Bunting. 2015. Evaluation of ALOS PALSAR data for high-resolution mapping of vegetated wetlands in Alaska. Remote Sensing 7:7272–7297.

Collins, M., et al. 2013. Long-term climate change: projections, commitments and irreversibility. Pages 1029–1136 *in* T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, editors. Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C., USA.

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P. P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology 28:2031–2064.

Dokuchaev, V. V. 1879. Mapping the Russian soils (in Russian). Imperial University of St. Petersburg, St. Petersburg, Russia.

Drake, T. W., K. P. Wickland, R. G. M. Spencer, D. M. McKnight, and R. G. Striegl. 2015. Ancient low–molecular-weight organic acids in permafrost fuel rapid carbon dioxide production upon thaw. Proceedings of the National Academy of Sciences USA. https://doi.org/10.1073/pnas.1511705112

Duffy, P. A., J. Epting, J. M. Graham, T. S. Rupp, and A. D. McGuire. 2007. Analysis of Alaskan burn severity patterns using remotely sensed data. International Journal of Wildland Fire 16:277–284.

Duffy, P. A., J. E. Walsh, J. M. Graham, D. H. Mann, and T. S. Rupp. 2005. Impacts of large-scale atmospheric-ocean variability on Alaskan fire season severity. Ecological Applications 15:1317–1330.

Euskirchen, E. S., A. D. McGuire, F. S. Chapin, S. Yi, and C. C. Thompson. 2009. Changes in vegetation in northern Alaska under scenarios of climate change, 2003–2100: implications for climate feedbacks. Ecological Applications 19:1022–1043.

Flannigan, M. D., B. J. Stocks, and B. M. Wotton. 2000. Climate change and forest fires. Science of the Total Environment 262:221–229.

Genet, H., Y. He, A. D. McGuire, Q. Zhuang, Y. Zhang, F. Biles, D. D'Amore, X. Zhou, and K. Johnson. 2016. Chapter 6. Terrestrial carbon modeling: baseline and projections in upland ecosystems. Pages 85–122 *in* Z. Zhu and A. D. McGuire, editors. Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of Alaska. USGS Professional Paper 1826. USGS, Reston, Virginia, USA. https://doi.org/10.3133/pp1826

Genet, H., et al. 2013. Modeling the effects of fire severity and climate warming on active layer thickness and soil carbon storage of black spruce forests across the landscape in interior Alaska. Environmental Research Letters 8:45016.

Gesch, D., M. Oimoen, S. Greenlee, C. Nelson, M. Steuck, and D. Tyler. 2002. The national elevation dataset. Photogrammetric Engineering and Remote Sensing 68:5–11.

Global Soil Data Task Group. 2000. Global gridded surfaces of selected soil characteristics (IGBP-DIS). Global gridded surfaces of selected soil characteristics (International Geosphere-Biosphere Programme—Data and Information System). Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://www.daac.ornl.gov

Goetz, S. J., A. G. Bunn, G. J. Fiske, and R. A. Houghton. 2005. Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance. Proceedings of the National Academy of Sciences USA 102:13521–13525.

Grosse, G., V. Romanovsky, T. Jorgenson, K. W. Anthony, J. Brown, and P. P. Overduin. 2011. Vulnerability and feedbacks of permafrost to climate change. EOS, Transactions American Geophysical Union 92:73–74.

Harden, J. W., et al. 2012. Field information links permafrost carbon to physical vulnerabilities of thawing. Geophysical Research Letters 39. https://doi.org/10.1029/2012GL051958

Harris, I., P. D. Jones, T. J. Osborn, and D. H. Lister. 2014. Updated high-resolution grids of monthly climatic observations—the CRU TS3.10 Dataset. International Journal of Climatology 34:623–642.

Harsch, M. A., P. E. Hulme, M. S. McGlone, and R. P. Duncan. 2009. Are treelines advancing? A global meta-analysis of treeline response to climate warming. Ecology Letters 12:1040–1049.

Hay, L. E., R. L. Wilby, and G. H. Leavesley. 2000. A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. Journal of the American Water Resources Association 36:387–397.

Hayhoe, K. A., 2010. A standardized framework for evaluating the skill of regional climate downscaled techniques. Dissertation. University of Illinois, Urbana-Champaign, Illinois, USA.

He, Y., H. Genet, A. D. McGuire, Q. Zhuang, B. K. Wylie, and Y. Zhang. 2016. Chapter 7. Wetland carbon dynamics in Alaska from 1950 to 2099. Pages 133–158 *in* Z. Zhu and A. D. McGuire, editors. Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of Alaska. USGS Professional Paper 1826. USGS, Reston, Virginia, USA. https://doi.org/10.3133/pp1826

Hély, C., Y. Bergeron, and M. D. Flannigan. 2000. Coarse woody debris in the southeastern Canadian boreal forest: composition and load variations in relation to stand replacement. Can. J. For. Res. 30:674–687. doi:10.1139/x99-256

Hinzman, L. D., et al. 2005. Evidence and implications of recent climate change in northern Alaska and other arctic regions. Climatic Change 72:251–298.

Hu, F. S., P. E. Higuera, J. E. Walsh, W. L. Chapman, P. A. Duffy, L. B. Brubaker, and M. L. Chipman. 2010. Tundra burning in Alaska: linkages to climatic change and sea ice retreat. Journal of Geophysical Research—Biogeosciences 115:G04002.

Jafarov, E. E., S. S. Marchenko, and V. E. Romanovsky. 2012. Numerical modeling of permafrost dynamics in Alaska using a high spatial resolution dataset. Cryosphere 6:613–624.

Jafarov, E. E., V. E. Romanovsky, H. Genet, A. D. McGuire, and S. S. Marchenko. 2013. The effects of fire on the thermal stability of permafrost in lowland and upland black spruce forests of interior Alaska in a changing climate. Environmental Research Letters 8:035030.

Jenny, H. 1941. Factors of soil formation: a system of quantitative pedology. Dover Publications, New York, New York, USA.

Johnson, K. D., J. W. Harden, A. David McGuire, M. Clark, F. Yuan, and A. O. Finley. 2013. Permafrost and organic layer interactions over a climate gradient in a discontinuous permafrost zone. Environmental Research Letters 8:035028.

Johnson, K. D., et al. 2011. Soil carbon distribution in Alaska in relation to soil-forming factors. Geoderma 167–168:71–84.

Johnston, C. E., S. A. Ewing, J. W. Harden, R. K. Varner, K. P. Wickland, J. C. Koch, C. C. Fuller, K. Manies, and M. T. Jorgenson. 2014. Effect of permafrost thaw on CO_2 and CH_4 exchange in a western Alaska peatland chronosequence. Environmental Research Letters 9:85004.

Johnstone, J. F., F. S. Chapin III, T. N. Hollingsworth, M. C. Mack, V. E. Romanovsky, and M. Turetsky. 2010. Fire, climate change, and forest resilience in interior Alaska. Canadian Journal of Forest Research 40:1302–1312.

Johnstone, J. F., T. S. Rupp, M. Olson, and D. Verbyla. 2011. Modeling impacts of fire severity on successional trajectories and future fire behavior in Alaskan boreal forests. Landscape Ecology 26:487–500.

Joly, K., P. A. Duffy, and T. S. Rupp. 2012. Simulating the effects of climate change on fire regimes in Arctic biomes: implications for caribou and moose habitat. Ecosphere 3:36.

Jones, B. M., G. Grosse, C. D. Arp, M. C. Jones, K. M. Walter Anthony, and V. E. Romanovsky. 2011. Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. Journal of Geophysical Research. Biogeosciences 116:G00M03.

Jones, B. M., G. Grosse, C. D. Arp, E. Miller, L. Liu, D. J. Hayes, and C. F. Larsen. 2015. Recent Arctic tundra fire initiates widespread thermokarst development. Scientific Reports 5:15865.

Jorgenson, M. T., V. M. Romanovsky, J. Harden, Y. Shur, J. O'Donnell, E. A. G. Schuur, M. Kanevskiy, and S. S. Marchenko. 2010. Resilience and vulnerability of permafrost to climate change. Canadian Journal of Forest Research 40:1219–1236.

Jorgenson, M. T., et al. 2013. Reorganization of vegetation, hydrology and soil carbon after permafrost degradation across heterogeneous boreal landscapes. Environmental Research Letters 8:035017.

Jorgenson, M. T., B. G. Marcot, D. K. Swanson, J. C. Jorgenson, and A. R. DeGange. 2015. Projected changes in diverse ecosystems from climate warming and biophysical drivers in northwest Alaska. Climatic Change 130:131–144. doi: 10.1007/s10584-014-1302-1

Juday, G. P., C. Alix, and T. A. Grant III. 2015. Spatial coherence and change of opposite white spruce temperature sensitivities on floodplains in Alaska confirms early-stage boreal biome shift. Forest Ecology and Management 350: 46–61.

Kasischke, E. S., N. L. Christensen, and B. J. Stocks. 1995. Fire, global warming, and the carbon balance of boreal forests. Ecological Applications 5:437–451.

Kasischke, E. S., et al. 2010. Alaska's changing fire regime: implications for the vulnerability of its boreal forests. Canadian Journal of Forest Research 40:1313–1324.

Kelly, R., M. L. Chipman, P. E. Higuera, I. Stefanova, L. B. Brubaker, and F. S. Hu. 2013. Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. Proceedings of the National Academy of Science USA 110:13055–13060.

Koven, C. D., et al. 2015. A simplified, data-constrained approach to estimate the permafrost carbon–climate feedback. Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences 373. https://doi.org/10.1098/rsta.2014.0423

Krawchuk, M. A., S. G. Cumming, M. D. Flannigan, and R. W. Wein. 2006. Biotic and abiotic regulation of lightning fire initiation in the mixedwood boreal forest. Ecology 87:458–468.

MacDougall, A. H., C. A. Avis, and A. J. Weaver. 2012. Significant contribution to climate warming from the permafrost carbon feedback. Nature Geoscience 5:719–721.

Mack, M. C., M. S. Bret-Harte, T. N. Hollingsworth, R. R. Jandt, E. A. G. Schuur, G. R. Shaver, and D. L. Verbyla. 2011. Carbon loss from an unprecedented Arctic tundra wildfire. Nature 475:489–492.

Mann, D. H., T. Scott Rupp, M. A. Olson, and P. A. Duffy. 2012. Is Alaska's Boreal Forest Now Crossing a Major Ecological Threshold? Arctic, Antarctic, and Alpine Research 44:319–331. doi:10.1657/1938-4246-44.3.319

Marchenko, S., V. Romanovsky, and G. Tipenko. 2008. Numerical modeling of spatial permafrost dynamics in Alaska, in: Proceedings of the Ninth International Conference on Permafrost. Institute of Northern Engineering, University of Alaska Fairbanks, pp. 1125–1130.

McGuire, A. D., L. G. Anderson, T. R. Christensen, S. Dallimore, L. Guo, D. J. Hayes, M. Heimann, T. D. Lorenson, R. W. Macdonald, and N. Roulet. 2009. Sensitivity of the carbon cycle in the Arctic to climate change. Ecological Monographs 79:523–555.

McGuire, A. D., J. M. Melillo, L. A. Joyce, D. W. Kicklighter, A. L. Grace, B. Moore III, and C. J. Vorosmarty. 1992. Interactions between carbon and nitrogen dynamics in estimating net primary productivity for potential vegetation in North America. Global Biogeochemical Cycles 6:101–124.

McGuire, A. D., T. S. Rupp, T. Kurkowski, and S. Stackpoole. 2016. Chapter 1. Introduction. Pages 1–158 *in* Z. Zhu and A. D. McGuire, editors. Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of Alaska. USGS Professional Paper 1826. USGS, Reston, Virginia, USA. https://doi.org/10.3133/pp1826

Meehl, G. A., C. Covey, K. E. Taylor, T. Delworth, R. J. Stouffer, M. Latif, B. McAvaney, and J. F. Mitchell. 2007. The WCRP CMIP3 multimodel dataset: A new era in climate change research. Bulletin of the American Meteorological Society 88:1383–1394.

Minsley, B. J., N. J. Pastick, B. K. Wylie, D. R. N. Brown, and M. A. Kass. 2016. Evidence for nonuniform permafrost degradation after fire in boreal landscapes. Journal of Geophysical Research—Earth Surface. https://doi.org/10.1002/2015JF003781

Myers-Smith, I. H., J. W. Harden, M. Wilmking, C. C. Fuller, A. D. McGuire, and F. S. Chapin III. 2008. Wetland succession in a permafrost collapse: interactions between fire and thermokarst. Biogeosciences 5:1273–1286.

Myers-Smith, I. H., et al. 2011. Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. Environmental Research Letters 6:045509.

Nakićenović, N., and R. Swart, editors. 2000. Special report on emissions scenarios—a special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

National Research Council. 2014. Opportunities to use remote sensing in understanding permafrost and related ecological characteristics: report of a workshop. National Academies Press, Washington, D.C., USA.

Nossov, D. R., M. T. Jorgenson, K. Kielland, and M. Z. Kanevskiy. 2013. Edaphic and microclimatic controls over permafrost response to fire in interior Alaska. Environmental Research Letters 8:035013.

Nowacki, G., P. Spencer, M. Fleming, T. Brock, and M. T. Jorgenson. 2003. Unified ecoregions of Alaska; 2001: U.S. Geological Survey Open-File Report 02–297, 1 map. U.S. Geological Survey, Anchorage, Alaska, USA.

Osterkamp, T. E., L. Viereck, Y. Shur, M. T. Jorgenson, C. Racine, A. Doyle, and R. D. Boone. 2000. Observations of thermokarst and its impact on boreal forests in Alaska, USA. Arctic, Antarctic, and Alpine Research 32:303–315.

Pastick, N. J., M. T. Jorgenson, B. K. Wylie, S. J. Nield, K. D. Johnson, and A. O. Finley. 2015*a*. Distribution of near-surface permafrost in Alaska: estimates of present and future conditions. Remote Sensing of Environment 168:301–315.

Pastick, N. J., M. T. Jorgenson, B. K. Wylie, S. J. Nield, K. D. Johnson, and A. O. Finley. 2015*b*. Probabilistic estimates of the distribution of near-surface (within 1 m) permafrost in Alaska: U.S. Geological Survey data release. https://doi.org/10.5066/F7C53HX6

Pastick, N. J., M. B. Rigge, B. K. Wylie, M. T. Jorgenson, J. R. Rose, K. D. Johnson, and L. Ji. 2014. Distribution and landscape controls of organic layer thickness and carbon within the Alaskan Yukon River Basin. Geoderma 230–231:79–94.

Pearson, R. G., S. J. Phillips, M. M. Loranty, P. S. A. Beck, T. Damoulas, S. J. Knight, and S. J. Goetz. 2013. Shifts in Arctic vegetation and associated feedbacks under climate change. Nature Climate Change 3:673–677.

Potter, C., S. Li, and R. Crabtree. 2013. Changes in Alaskan tundra ecosystems estimated from MODIS greenness trends, 2000 to 2010. Journal of Geophysics & Remote Sensing 2:107.

Riordan, B., D. Verbyla, and A. D. McGuire. 2006. Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. Journal of Geophysical Research—Biogeosciences 2005–2012:111.

Roach, J., B. Griffith, D. Verbyla, and J. Jones. 2011. Mechanisms influencing changes in lake area in Alaskan boreal forest. Global Change Biology 17:2567–2583.

Romanovsky, V., M. Burgess, S. Smith, K. Yoshikawa, and J. Brown. 2011. Permafrost temperature records: indicators of climate change. EOS, Transactions American Geophysical Union 83:589.

Romanovsky, V. E., S. L. Smith, and H. H. Christiansen. 2010. Permafrost thermal state in the polar Northern Hemisphere during the International Polar Year 2007–2009: a synthesis. Permafrost and Periglacial Processes 21:106–116.

Rupp, T. S., F. S. I. Chapin, and A. M. Starfield. 2001. Modeling the influence of topographic barriers on treeline advance at the forest-tundra ecotone in northwestern Alaska. Climatic Change 48:399–416.

Rupp, T. S., P. Duffy, M. Leonawicz, M. Lindgren, A. Breen, T. Kurkowski, A. Floyd, A. Bennett, and L. Krutikov. 2016. Chapter 2. Climate scenarios, land cover, and wildland fire. Pages 17–52 *in* Z. Zhu and A. D. McGuire, editors. Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of Alaska. USGS Professional Paper 1826. USGS, Reston, Virginia, USA. https://doi.org/10.3133/pp1826

Rupp, T. S., A. M. Starfield, and F. S. Chapin III. 2000. A frame-based spatially explicit model of subarctic vegetation response to climatic change- comparison with a point model. Landscape Ecology 15:383–400.

Rupp, T. S., A. M. Starfield, F. S. Chapin, and P. Duffy. 2002. Modeling the impact of black spruce on the fire regime of Alaskan boreal forest. Climatic Change 55:213–233.

Schuur, E. A. G., J. G. Vogel, K. G. Crummer, H. Lee, J. O. Sickman, and T. E. Osterkamp. 2009. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. Nature 459:556–559.

Schuur, E. A. G., et al. 2015. Climate change and the permafrost carbon feedback. Nature 520:171–179.

Serreze, M. C., J. E. Walsh, F. S. C. Iii, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W. C. Oechel, J. Morison, T. Zhang, and R. G. Barry. 2000. Observational evidence of recent change in the northern high-latitude environment. Climatic Change 46:159–207.

Shulski, M., and G. Wendler. 2007. The climate of Alaska. Pages 208. University of Alaska Press, Fairbanks, Alaska, USA.

Soil Survey Staff. 2012. General soil map of Alaska—STATSGO data: Natural Resources Conservation Service, United States Department of Agriculture, Web Soil Survey. http://websoilsurvey.nrcs.usda.gov/

Stackpoole, S., D. Butman, D. Clow, K. Verdin, B. Gaglioti, and R. Striegl. 2016. Chapter 8. Carbon burial, transport, and emission from inland aquatic ecosystems in Alaska. Pages 158–188 *in* Z. Zhu and A. D. McGuire, editors. Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of Alaska. USGS Professional Paper 1826. USGS, Reston, Virginia, USA. https://doi.org/10.3133/pp1826

Stewart, B. C., K. E. Kunkel, L. E. Stevens, L. Sun, and J. E. Walsh. 2013. Regional climate trends and scenarios for the U.S. National Climate Assessment: part 7. Climate of Alaska. NOAA Technical Report NESDIS 142-7. 60 pp. U.S. Department of Commerce, Washington, D.C., USA.

Streletskiy, D. A., N. I. Shiklomanov, F. E. Nelson, and A. E. Klene. 2013. Thirteen years of observations at Alaskan CALM sites: long-term active layer and ground surface temperature trends. Pages 1727–1732 *in* D. L. Kane and K. M. Hinkel, editors. Ninth International Conference on Permafrost. Institute of Northern Engineering, University of Alaska Fairbanks, Fairbanks, Alaska, USA.

Streletskiy, D. A., N. I. Shiklomanov, J. D. Little, F. E. Nelson, J. Brown, K. E. Nyland, and A. E. Klene. 2016. Thaw subsidence in undisturbed tundra landscapes, barrow, Alaska, 1962–2015. Permafrost and Periglacial Processes. https://doi.org/10.1002/ppp.1918

Turetsky, M. R., E. S. Kane, J. W. Harden, R. D. Ottmar, K. L. Manies, E. Hoy, and E. S. Kasischke. 2011. Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. Nature Geoscience 4:27–31.

Turetsky, M. R., R. K. Wieder, D. H. Vitt, R. J. Evans, and K. D. Scott. 2007. The disappearance of relict permafrost in boreal North America: effects on peatland carbon storage and fluxes. Global Change Biology 13:1922–1934.

Veraverbeke, S., B. M. Rogers, and J. T. Randerson. 2015. Daily burned area and carbon emissions from boreal fires in Alaska. Biogeosciences Discussions 12:3579–3601.

Verbyla, D. 2008. The greening and browning of Alaska based on 1982–2003 satellite data. Global Ecology and Biogeography 17:547–555.

Walker, D. A., et al. 2009. Spatial and temporal patterns of greenness on the Yamal Peninsula, Russia: interactions of ecological and social factors affecting the Arctic normalized difference vegetation index. Environmental Research Letters 4:045004.

Walsh, J. E., W. L. Chapman, V. Romanovsky, J. H. Christensen, and M. Stendel. 2008. Global climate model performance over Alaska and Greenland. Journal of Climate 21:6156–6174.

Walvoord, M. A., C. I. Voss, and T. P. Wellman. 2012. Influence of permafrost distribution on groundwater flow in the context of climate-driven permafrost thaw—example from Yukon Flats Basin, Alaska, United States. Water Resources Research 48:W07524.

Whitcomb, J., M. Moghaddam, K. McDonald, J. Kellndorfer, and E. Podest. 2009. Mapping vegetated wetlands of Alaska using L-band radar satellite imagery. Canadian Journal of Remote Sensing 35:54–72.

Wolken, J. M., et al. 2011. Evidence and implications of recent and projected climate change in Alaska's forest ecosystems. Ecosphere 2:35.

Wylie, B. K., N. J. Pastick, K. D. Johnson, B. Bliss, and H. Genet. 2016. Chapter 3. Soil carbon, and permafrost estimates and susceptibility in Alaska, Pages 52–76 *in* Z. Zhu and A. D. McGuire editors. Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of Alaska. USGS Professional Paper 1826. USGS, Reston, Virginia, USA. https://doi.org/10.3133/pp1826

Yi, S., A. D. McGuire, E. Kasischke, J. Harden, K. Manies, M. Mack, and M. Turetsky. 2010. A dynamic organic soil biogeochemical model for simulating the effects of wildfire on soil environmental conditions and carbon dynamics of black spruce forests. Journal of Geophysical Research—Biogeosciences 115:G04015.

Yi, S., et al. 2009. Interactions between soil thermal and hydrological dynamics in the response of Alaska ecosystems to fire disturbance. Journal of Geophysical Research—Biogeosciences 114:20.

Yoshikawa, K., W. R. Bolton, V. E. Romanovsky, M. Fukuda, and L. D. Hinzman. 2002. Impacts of wildfire on the permafrost in the boreal forests of interior Alaska. Journal of Geophysical Research—Atmospheres 107:14.

Yoshikawa, K., and L. D. Hinzman. 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. Permafrost and Periglacial Processes 14:151–160.

Young, A. M., P. E. Higuera, P. A. Duffy, and F. S. Hu. 2016. Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. Ecography. https://doi.org/10.1111/ecog.02205

Zhang, Y., I. Olthof, R. Fraser, and S. A. Wolfe. 2014. A new approach to mapping permafrost and change incorporating uncertainties in ground conditions and climate projections. Cryosphere 8:1895–1935.

Zhu, Z., and A. D. McGuire, editors. 2016. Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of Alaska. U.S. Geological Survey Professional Paper 1826. USGS, Reston, Virginia, USA. https://doi.org/10.3133/pp1826

Zhuang, Q., J. M. Melillo, D. W. Kicklighter, R. G. Prinn, A. D. McGuire, P. A. Steudler, B. S. Felzer, and H. Shaomin. 2004. Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: a retrospective analysis with a process-based biogeochemistry model. Global Biogeochemical Cycles 18: GB3010.

Zhuang, Q., J. M. Melillo, A. D. McGuire, D. W. Kicklighter, R. G. Prinn, P. A. Steudler, B. S. Felzer, and S. Hu. 2007. Net emissions of CH_4 and CO_2 in Alaska- implications for the region's greenhouse gas budget. Ecological Applications 17:203–212.

Zona, D., et al. 2016. Cold season emissions dominate the Arctic tundra methane budget. Proceedings of the National Academy of Sciences 113:40–45.

Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.1538/full