Chapter 3. Soil Carbon and Permafrost Estimates and Susceptibility to Climate Change in Alaska

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3.1. Highlights

- Several soil carbon and permafrost data products in Alaska, either produced for this assessment or available from the literature, were evaluated to synthesize observation-based estimates of distributions of soil organic carbon (SOC), permafrost, and other variables. The synthesis was also compared to simulated estimates by an ecosystem carbon dynamic model called DOS-TEM (Dynamic Organic Soil version of the Terrestrial Ecosystem Model).

- The total SOC storage in boreal and arctic regions in Alaska ranged from 31 to 72 petagrams of carbon (PgC) among different mapped products, and SOC simulated by DOS-TEM was well within this range at 46 PgC (with a standard deviation [s.d.] of 22 PgC).

- Near-surface (within 1 meter [m]) permafrost (NSP) was estimated to underlie 36 to 67 percent of Alaska among different map products used in the evaluation, and NSP simulated by DOS-TEM was within this range at 44 percent. Furthermore, DOS-TEM simulations of NSP fell within the range of map product estimates for 87 percent of ecotypes, and outlier ecotypes constitute approximately 16 percent of Alaska.

- Average active-layer thickness (ALT) ranged from 76 to 84 centimeters (cm) from surface among different mapped products, and ALT simulated by DOS-TEM was slightly outside of this range at 86 ± 8 cm, but within the range of map product uncertainty. The ALT derived from the state soil geographic database (STATSGO) was generally higher than other estimates, possibly owing to how ALT is described in soil pedon datasets and measured in the field.

- Organic soils were estimated to underlie 8 to 30 percent of Alaska among different map products, and organic soil simulations by DOS-TEM were within this range at 18 percent.

- A simple conceptual model of soil susceptibility to climate change indicated that Arctic Landscape Conservation Cooperative (LCC) lowland shrub tundra and Western Alaska LCC lowland shrub tundra ecotypes are highly susceptible to climate change because of large and potentially liable frozen and unfrozen SOC stocks.

- Intermediate susceptible ecotypes were Arctic LCC upland shrub and graminoid tundra with susceptibility being driven by potential changes to continuous NSP extent and the lack of thick insulating layers of organic soils.

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3.2. Conceptual Discussion of Roles and State of the Knowledge About Soil Carbon and Permafrost in Boreal and Arctic Ecosystems

There are large accumulations of soil organic carbon in arctic and boreal forest ecosystems. Hugelius and others (2014) indicated that the northern permafrost regions of the world contain approximately 1,300 petagrams of organic carbon (PgC), of which 800 PgC (61 percent) occurs in perennially frozen soils and deposits. For comparison, the amount of carbon as carbon dioxide (CO_2) currently in the atmosphere is approximately 800 PgC, of which 240 PgC represents the net accumulation in the atmosphere from fossil-fuel and land-use emissions between 1750 and 2011 (Stocker and others, 2013). Thus, the carbon in permafrost-affected ground is nearly double the carbon in the atmosphere. The thaw and decay of permafrost and permafrost carbon will be irreversible with the onset of warming trend of the 2014 and 2100 timeframes, and the release of this carbon (the permafrost carbon feedback) is not currently accounted for in the climate models used by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Stocker and others, 2013). Accounting for this additional carbon will require larger reductions in fossil-fuel emissions to reach a target atmospheric CO_2 concentration and therefore a target limit on global temperature increase (Schaefer and others, 2011).

To estimate the quantity of soil organic carbon in Alaska, Johnson and others (2011) compiled data for many soil profile measurements and evaluated the distributions of soil carbon by climate regions, landforms, ecoregions, and ecosystem types. Bliss and Maursetter (2010) estimated a total of 48 PgC of soil organic carbon for Alaska and Mishra and Riley (2012) estimated 77 PgC, with these estimates influenced by assumptions and data availability for deeper soils (for example, between 1 and 3 meters [m]). Although these soil carbon inventory studies largely used the same soil carbon measurements, with slight variations and additions between assessments, each study made use of different upscaling approaches.

The status of the permafrost system can be measured using deep boreholes with accurate measurements of the change of temperature with depth through the Global Terrestrial Network for Permafrost (GTN–P; Clow, 2014). The thickness of the active layer (that is, maximum annual thaw depth) is another measure for the status of the permafrost system. With warmer temperatures, the thickness of the active layer is expected to increase. Although point-based measurements are useful for understanding local permafrost dynamics, these measurements are typically sparse and there is an increasing need to monitor and map permafrost properties at larger scales (National Research Council, 2014). As part of an international network of Circumpolar Active Layer Monitoring (CALM) sites, Hinkel and Nelson (2003) concluded that in Alaska, active-layer thickness is correlated with inter-annual variability in summer temperature and that local variations in active-layer thickness and near-surface soil moisture are influenced by vegetation, substrate properties, snow cover dynamics, and terrain. More recently, empirical models have also been used to relate permafrost and soil characteristics to environmental factors for regional-scale mapping. For instance, remotely sensed or derived datasets have been combined with digital elevation models and field data to map permafrost properties over large areas of Alaska (Pastick and others, 2013; Pastick, Jorgenson, and others, 2014).

Time-series analyses of aerial photos and remote sensing imagery are also useful for understanding the rate and extent of change associated with permafrost degradation. Using aerial photo analyses, Jorgenson and others (2001) found that in the Tanana Flats in central Alaska, permafrost degradation has been widespread and rapid, causing large shifts in ecosystems from birch forests to fens and bogs. With warming, areas that are ice-rich experience a collapse of the surface topography (thermokarst) on the order of 1 to 1.5 m. In arctic Alaska, Jorgenson and others (2006) found that recent degradation has mainly affected massive wedges of ice that previously had been stable for thousands of years. Thermokarst potentially can affect 10 to 30 percent of arctic lowland landscapes and severely alter tundra ecosystems even with modest climate warming (Jorgenson and others, 2006). Additionally, approximately 40 percent of subarctic Alaska may also be susceptible to permafrost degradation and thermokarst (Jorgenson and others, 2008).

A variety of methods are used to understand the potential rate of carbon release with warming, including chronosequences (Johnston and others, 2014), flux studies on wetland gradients (McConnell and others, 2013), incubation of soil samples (Wickland and Neff, 2008; Mu and others, 2014; Treat and others, 2014), and manipulations that artificially warm the soil (Natali and others, 2011, 2012). The insulating effect of moss may depend on the water content (O'Donnell and others, 2009). Microtopography and slope may influence groundwater and surface water flow and thus the formation of taliks, thermokarst ponds, and pond drainage (Yoshikawa and Hinzman, 2003; Osterkamp and others, 2009; Wellman and others, 2013).

Schaefer and others (2014) synthesized results from 14 studies projecting the magnitude of the permafrost carbon feedback across the pan-Arctic to the year 2100, and found an ensemble average of 120 ± 85 PgC and a median of 100 PgC. There is considerable uncertainty from the variety of methods and assumptions, but this amount of carbon would be equivalent to 5.7 percent of projected anthropogenic emissions through 2100 (IPCC scenario RCP 8.5; Riahi and others, 2011), and would increase global temperatures by 0.29 ± 0.21 degrees Celsius (°C), or 7.8 ± 5.7 percent. Projections indicate that 60 percent of the permafrost emissions will occur after 2100, so releases of greenhouse gases from thawing permafrost will continue for centuries. Schuur and others (2015) suggest a similar median magnitude for the permafrost carbon feedback with evidence for a gradual and prolonged release of greenhouse-gas emissions in a warming climate, and present a research strategy for reducing the uncertainties. Schaefer and others (2011) suggest that the Arctic as a whole may change from a carbon sink to a carbon source after the mid-2020s.

Structural and functional changes in boreal forest ecosystems associated with warming (for example, reduced growth of dominant tree species, plant disease and insect outbreaks, warming and thawing of permafrost, and increased wildfire extent) that are unprecedented in the past 6,000 years are expected over the next few decades (Chapin and others, 2010; Euskirchen and others, 2010). A shift from coniferous to deciduous vegetation in Alaska began about 1990 (Mann and others, 2012), and there has also been a documented increase in the frequency, intensity, and extent of fire disturbance associated with warming and drying trends (Kasischke and others, 2010).

Fire directly releases carbon from ecosystems, and resulting changes in heat absorption and organic-layer thickness influence the degradation and (or) reformation of permafrost. Large fires have become more frequent in recent years in interior Alaska, with 17 percent of the land area burning in a decade (Barrett and others, 2011). Barrett and others (2011) estimated that 39 percent (approximately 4,000 square kilometers [km^2]) of all burned black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.) stands in 2004 had less than 10 centimeters (cm) of residual organic layer, which may lead to a post-fire loss of permafrost and high-quality seedbeds better suited for the establishment of deciduous species. With a severe fire, the trees and moss will be killed, leaving a blackened soil surface that absorbs sunlight directly onto the soil, transferring heat into the soil and thawing permafrost (Genet and others, 2013). Harden and others (2006) found that for every centimeter of soil organic-layer thickness, the temperature at 5-cm depth was about 0.5 °C cooler in summer months. Turetsky and others (2011) indicate that some black spruce stands have become a net source of carbon to the atmosphere, and Chambers and Chapin (2002) show there can be an initial reduction of minimum albedo following fire from 0.09 to 0.06, followed by a rapid increase to 0.135 as the vegetation increased. Increases in fire disturbance will augment the amount of carbon released to the atmosphere and thus contribute to climate warming, and shifts in species composition also have the potential to influence the regional climate by changing surface albedo and rates of evapotranspiration and conductance (Amiro and others, 2006).

From the conceptual description above, it is shown that to properly represent the spatial and temporal variability of soil carbon stocks in high-latitude ecosystems, process-based ecosystem models need to (1) correctly initialize soil carbon stocks and permafrost distribution as a function of drainage conditions, soil properties (for example, texture, organic-layer thickness), and vegetation composition and (2) represent the effects of climate and disturbance regimes on permafrost dynamics and the consequences on soil carbon stocks over time. One way to evaluate how well process-based ecosystem models simulate regional ecological processes and estimate the spatial and temporal variability of soil properties is by comparing modeled outputs to a set of data products developed using other methods and observations, as is described below.

3.3. Objectives of the Study and General Methods

As part of this assessment, one objective of this chapter is a synthesis of available current and new data products of permafrost distribution and soil carbon in Alaska. Several new soil property products were created as part of this study to help improve and refine soil property estimates, to increase the number of product versions beyond the existing spatial products, and to better quantify and assess landscape-scale map uncertainties. The new soil property products incorporated new field data, higher resolution inputs layers, and (or) different mapping algorithms relative to previous studies. Statistical-empirical techniques were used in the development of new products to quantify near-surface soil properties throughout Alaska. The convergence of multiple products derived from observations, both in terms of spatial patterns and quantification of uncertainties, was the basis for a confidence measure used for the evaluation of a process-based model (that is, DOS-TEM). Multiproduct comparisons reduce the consequences of both false-positive and false-negative results that may occur when only one reference product is used.

The second objective of this chapter is to evaluate how well processes related to the spatial distribution of soil properties were represented in the biogeochemical process-based model used in this assessment by observing the differences between the model and the mapped products. The Dynamic Organic Soil version of the Terrestrial Ecosystem Model (DOS-TEM) is a large-scale ecosystem model designed to study interactions among carbon and nitrogen cycling, vegetation composition, and the effects of climate change and disturbances on soil physical properties, including permafrost and active-layer dynamics. Over the last two decades, DOS-TEM has been developed to simulate biogeochemical cycles and vegetation dynamics in high latitudes, including development of an environmental module to reproduce the thermal and hydrological regimes of the organic and mineral layers in permafrost soils (Zhuang and others, 2003; Yi and others, 2009). The DOS-TEM model is a widely used model for high-latitude boreal and arctic systems and one of the primary models used in this Alaska assessment for current and future fluxes and stock of carbon. The synthesis provided in the present chapter was designed to provide a baseline to evaluate how DOS-TEM reproduced the spatial variability of historical soil carbon and permafrost distribution in Alaska compared to other empirical and process-based models. DOS-TEM used a soil texture data source independent of datasets (see chapter 6) discussed in this chapter because of an issue with timing. The state soil geographic database (STATSGO) soil texture maps were not available at the time DOS-TEM simulations began. Chapters 6 and 7 present how DOS-TEM represents the temporal variability of soil carbon stocks and permafrost.

The final objective of this chapter was to develop a simple conceptual model and map of soil relative susceptibility to climate change based on expert knowledge, new soil and ecotype maps, and the literature. Here we define relative susceptibility as the degree to which particular “ecotypes” (that is, combinations of ecoregion [Landscape Conservation Cooperative, LCC region], upland or lowland, and land-cover type) and soils are open, liable, or sensitive to climate stimuli (Smit and others, 1999). The results of this analysis will be informative for land use and land management decision making and provide actionable science information for sustainable resource management practices.

3.4. Methods and Analysis of Soil Products

Statistical and geospatial methods were used to produce and examine spatially explicit estimates of near-surface soil properties (that is, soil organic carbon, SOC; permafrost distribution; active-layer thickness, ALT; and organic-layer thickness, OLT) throughout Alaska, although parameters related to permafrost and soil carbon were not assessed in the North Pacific LCC because (1) permafrost occurrence in this region is typically rare, (2) a portion of the spatial datasets did not cover this region, and (3) carbon simulation results were not available at the time of these analyses and were being done separately for this report (see chapter 4). The newly generated products were then compared with other existing assessments. Accuracy assessments were conducted for a portion of these map products, but accuracies can’t be directly compared because of model and mapping differences. Because the various products were generated at different resolutions and with different mapping methods, comparisons were conducted at the ecotype level. DOS-TEM outputs were compared to the means, ranges, and uncertainties of the other spatial products within ecotype units. Masked areas or areas with no data were excluded from ALT and OLT comparisons. Ecotypes are broad strata that can have significant soil carbon and permafrost variability related to adjacency to water, soil texture, and effect of fire. Uncertainty was characterized in three ways: (1) as the mean absolute difference (MAD) from the ecotype mean, (2) as the data range of the spatial product means for each ecotype, and (3) as the difference between product ecotype means and respective DOS-TEM ecotype means. We employ convergence of evidence in our analysis approach, but acknowledge that the true value can potentially be one of the outliers. The ecotype product means (excluding DOS-TEM) were used to develop six ecologically based sensitivity criteria. A simple susceptibility index was developed related to an inter-criteria score (sum of 0 [false] or 1 [true] across the six criteria) and the potential area affected, as is further described in section 3.4.4. Environmental factors controlling the distribution of near-surface soil properties and distributions are also briefly highlighted and discussed.

It is also important to note that all empirically derived products rely heavily on the same soil pedon dataset (with varying additions of other field data and albeit different extrapolation methods) but these observations are not a systematic or random sample of Alaska’s ecotypes. Thus, some ecotypes are poorly represented whereas others are fairly well represented, which creates a source of uncertainty between ecotypes that is difficult to quantify (Johnson and others, 2011). For example, the Western Alaska LCC has the lowest representation of soil carbon observations, having a sample density of 2, 8, and 15 times lower than the Northwest Boreal LCC North, Arctic LCC, and Northwest Boreal LCC South, respectively. Thus, soil carbon estimates of the Western Alaska LCC should qualitatively be considered the most uncertain compared to other regions.

3.4.1. Soil Organic Carbon

For the analysis of multiple products conducted for this assessment, the available SOC products included two new SOC maps and several existing maps (table 3.1).

The JOHNSON SOC product (fig. 3.1*A*) developed by Johnson and others (2011) and modified for the present report was created using 724 soil pedon observations. Soil pedon data sources included data from the U.S. Geological Survey (USGS) and the National Resources Conservation Service (NRCS) and a variety of data available from the Bonanza Creek Long Term Ecological Research (LTER) Web site. The SOC was estimated for the surface organic layer (OL), the mineral soil to a 1-m depth below the OL (MIN1m), and the total organic plus mineral soils (OL+MIN1m). These three soil carbon pools are directly comparable to DOS-TEM outputs. Additionally, the OL and MIN1m pools were partitioned into frozen and unfrozen components based on horizon designation (that is, the presence or absence of the “f” suffix). Frozen and unfrozen soil carbon were used to analyze the vulnerability of SOC loss from thawing permafrost and associated decomposition. Cryoturbated organic horizons were included as mineral soil. The means of the components (and their totals) were scaled up to land-cover types using the methods described in Hugelius and others (2012). A total of 33 land-cover types were derived for the soil carbon analysis from a landform map (Johnson and others, 2011), National Land Cover Database (NLCD) vegetation cover (Homer and others, 2004), and additional information on white spruce (*Picea glauca* (Moench) Voss) distribution from LANDFIRE (2008). These carbon statistics were crosswalked to the ecotypes in this study using similar land-cover types with large areas in each ecotype.

The STATSGO SOC data layer was developed from the 1:500,000-scale state soil geographic database (STATSGO) for Alaska (Soil Survey Staff, 2012), using expert knowledge

Table 3.1. Summary of spatial products and process-based model evaluated for soil organic carbon (SOC) in this assessment.

[STATSGO, state soil geographic database; NCSCDv2, Northern Circumpolar Soil Carbon Database version 2; CAVM, Circumpolar Arctic Vegetation Map; DOS-TEM, Dynamic Organic Soil version of the Terrestrial Ecosystem Model; OL, surface organic layer; MIN1m, mineral soil to 1-meter depth below the bottom of the surface organic layer; OL+MIN1m, the sum of OL and MIN1m]

Product name	Extent	Resolution	Method	Depth	Reference
JOHNSON	Alaska	1 kilometer	Means extrapolated to raster	OL, MIN1m, OL+MIN1m	Johnson and others (2011) and this report
STATSGO	Alaska	1 kilometer	Means extrapolated to polygons	OL, MIN1m, OL+MIN1m	This report
MISHRA	Alaska	60 meter	Geostatistical	"whole profile"	Mishra and Riley (2012)
NCSCDv2	Boreal and arctic Alaska	0.012°	Means extrapolated to polygons	0 to 152 centimeters	Hugelius and others (2013)
CAVM	Arctic Alaska	1 kilometer	Means extrapolated to polygons	OL, 0 to 1 meter	Ping and others (2008)
DOS-TEM	Alaska	1 kilometer	Process-based model	OL, MIN1m, OL+MIN1m	This report

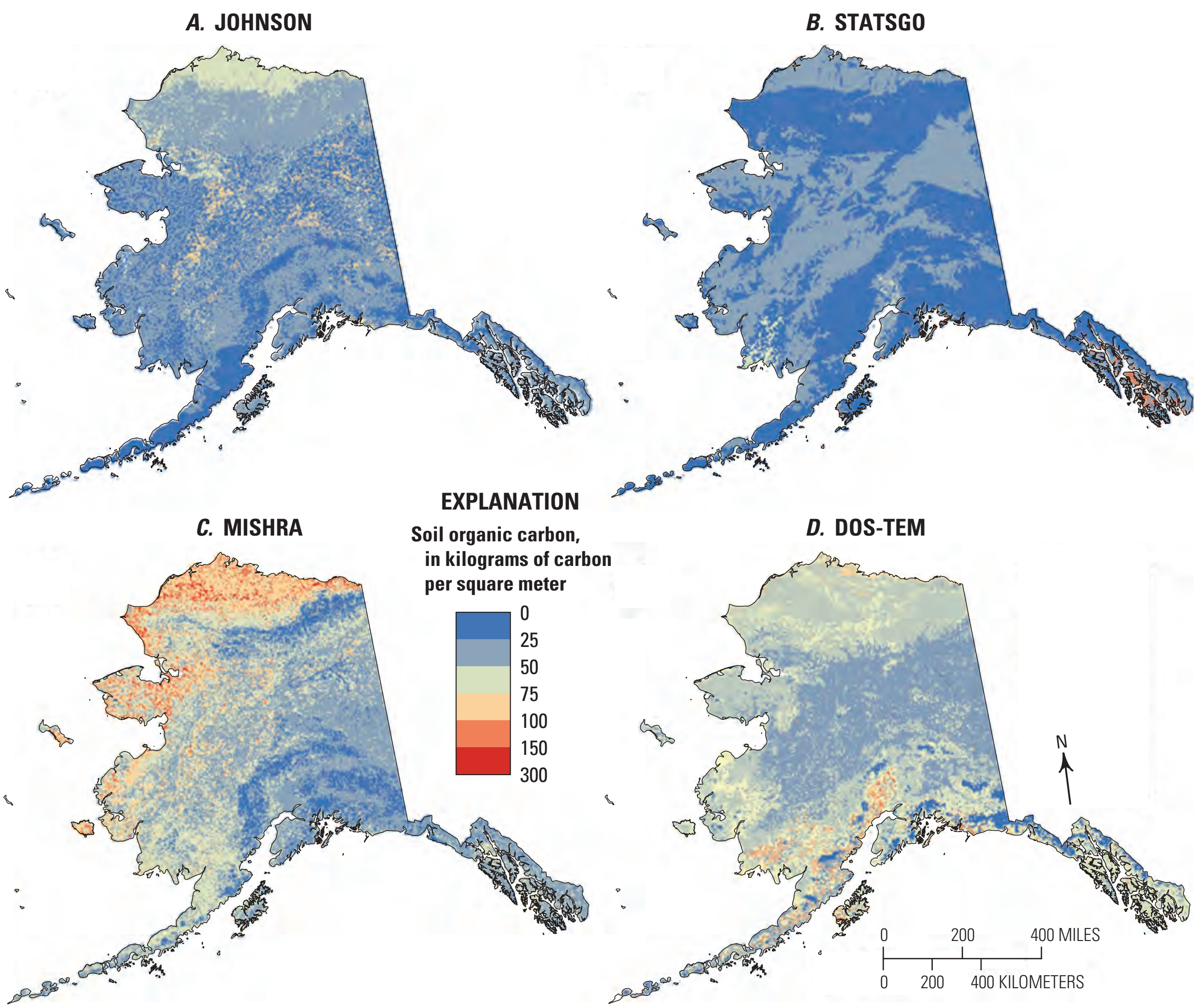

Figure 3.1. Total profile soil organic carbon (SOC) for those products used in the assessment that covered all of Alaska. *A*, SOC from Johnson and others (2011). *B*, SOC derived from the state soil geographic database (STATSGO). *C*, SOC from Mishra and Riley (2012). *D*, SOC simulated by the Dynamic Organic Soil version of the Terrestrial Ecosystem Model (DOS-TEM).

to extrapolate NRCS soil pedon observations and rasterized to 1-kilometer (km) resolution. The SOC was computed for each horizon from the representative organic matter attribute (om_r) by converting organic matter to organic carbon with a 0.58 factor and accounting for rock fragments. A map unit average soil carbon in kilograms of carbon per square meter (kgC/m^2) was computed for each analysis depth zone (for example, OL or OL+MIN1m) by accumulating across horizons and components with the mass of soil and the component percentage (comppct_r) as weighting factors with methods following Bliss and others (2014) (fig. 3.1*B*).

Several other existing products were available for comparisons of SOC density or SOC totals. The MISHRA SOC product (fig. 3.1*C*) represents "whole profile from the surface to the C horizon" SOC predicted from topographic, land-cover type, geologic, and climate data and 472 soil profiles for all of Alaska at a 60-m resolution (Mishra and Riley, 2012). In contrast to the other products of this study, it is the only one to use a geostatistical approach (geographically weighted regression). The Northern Circumpolar Soil Carbon Database version 2 (NCSCDv2) SOC product assigns mean SOC values to a compilation of soil polygon maps for the whole circumpolar arctic but does not include southeastern Alaska (Hugelius and others, 2013). The data are reported by meter depth (that is, 0–100 cm, 100–200 cm, and 200–300 cm) but for comparability to the other products of this study the first two depths were converted to represent SOC to usually the 152-cm depth, or the C horizon. The CAVM SOC product is similar to other SOC products mentioned in this study in that mean SOC values were assigned to land-cover types for upscaling (Ping and others, 2008). However, land-cover types were determined from a separate map, the Circumpolar Arctic Vegetation Map (CAVM), and only cover the Arctic LCC and the Aleutian and Bering Sea Islands LCC ecoregions.

The DOS-TEM SOC product (fig. 3.1*D*) provides estimates of SOC in the organic layer and the mineral soil (down to 1 m below the OL) separately. DOS-TEM simulates the dynamic changes of the SOC pools as a result of the incorporation of the litterfall to the soil, the carbon loss from decomposition by microbes, and combustion during wildfire. Therefore, soil carbon pools in DOS-TEM depend mainly on climate history, drainage conditions, vegetation productivity, and the fire regime (frequency and intensity). DOS-TEM estimates of SOC are provided at a 1-km resolution for the entire State. Readers are referred to Yi and others (2010) for a description of the processes that drive soil carbon dynamics in DOS-TEM. The DOS-TEM output at spin-up (models are run repetitively to get equilibrium conditions) were selected for the comparisons shown in this section.

3.4.2. Permafrost and Active-Layer Thickness

For the multiple product analysis of this report, the available permafrost products included three new permafrost maps and one existing map (table 3.2).

The "LANDCARBON" (products produced in this assessment) permafrost and associated ALT map products were developed using machine learning algorithms (that is, regression and classification trees) that spatially and statistically extended late-season field observations (sample size [n] ~17,000), collected from 1990 to 2013, for the mapping of near-surface permafrost (NSP, within the upper 1 m of the soil column) throughout Alaska (Pastick and others, 2015). This approach made use of remotely sensed, climatic, and biophysical geospatial data to produce moderate-resolution (30-m pixel) maps of the presence or absence of NSP, probability of NSP, and ALT (seasonal maximum depth of the permafrost) (figs. 3.2*A*, 3.3, and 3.4*A*). Readers are referred to Pastick and others (2015) for a detailed discussion of those data and methods used to derive and assess the map products. Climate variables (that is, mean annual air temperature, length of growing season, annual and winter precipitation) were identified to be the most important environmental factors controlling landscape-level distributions of permafrost. Whereas climate was identified to have first-order controls on landscape NSP distributions, permafrost-climate-ecological interactions are scale dependent. Remotely sensed or mapped data were also an influential predictor in the model and suggested that certain surface features (that is, vegetation, topography) are also good indicators of NSP properties. Accuracy assessments consisted of independent test datasets and f-fold cross-validations (Martin and others, 2011). Cross-validation and independent test accuracies indicated that the NSP map had an overall accuracy of 85 percent (95-percent confidence interval [CI]: 84.7, 85.8). Independent tests showed that the ALT map had a mean average error (MAE), mean bias error (MBE), relative mean average error (rMAE), relative mean bias error (rMBE), and Pearson's correlation coefficient of 15 cm, 0 cm, 27 percent, 0 percent, and 0.61, respectively.

The STATSGO permafrost estimates of the presence or absence of NSP were computed by evaluating the texture designation for the horizon at 100-cm depth. If the horizon was designated as "frozen" ("PF" in the texture code), then the component was flagged as having NSP. If the sum of the component percentages flagged in this way was at least 50 percent, then the map unit was coded as having NSP "present" and if it was less than 50 percent, then permafrost was considered "absent" (fig. 3.2*B*). The ALT for a component was the depth of the soil at the top of a permanently frozen soil horizon. If permafrost was not present in the component or the permafrost was deeper than 100 cm, then the ALT for the component was set to 101 cm for comparability of methods with other datasets being evaluated in this study. A weighted average of ALT was computed with the component percentage as the weighting factor and assigned to the map units, as shown in figure 3.4*B*.

The GIPL 1.3 permafrost products were made using the University of Alaska-Fairbanks, Geophysical Institute Permafrost Laboratory (GIPL; 2011) version 1.3 transient model. The GIPL 1.3 spatial transient model simulates

Table 3.2. Summary of spatial products and process-based model evaluated for permafrost in this assessment.

[LANDCARBON, data product developed for this assessment; STATSGO, state soil geographic database; GIPL 1.3, Geophysical Institute Permafrost Laboratory version 1.3 transient model; DOS-TEM, Dynamic Organic Soil version of the Terrestrial Ecosystem Model]

Product name	Extent	Resolution	Method	Near-surface permafrost depth threshold	Time period	Reference
LANDCARBON	Alaska	30 meter	Machine learning	1 meter	1990–2013	Pastick and others (2015) and this report
STATSGO	Alaska	1 kilometer	Means extrapolated to polygons	1 meter	Not specified (expert judgment in 2012)	This report
GIPL 1.3	Alaska	2 kilometer	Process-based model	1 meter	2000–2009	Marchenko and others (2008)
DOS-TEM	Alaska (excluding the North Pacific Landscape Conservation Cooperative)	1 kilometer	Process-based model	1 meter	1950–1960	This report

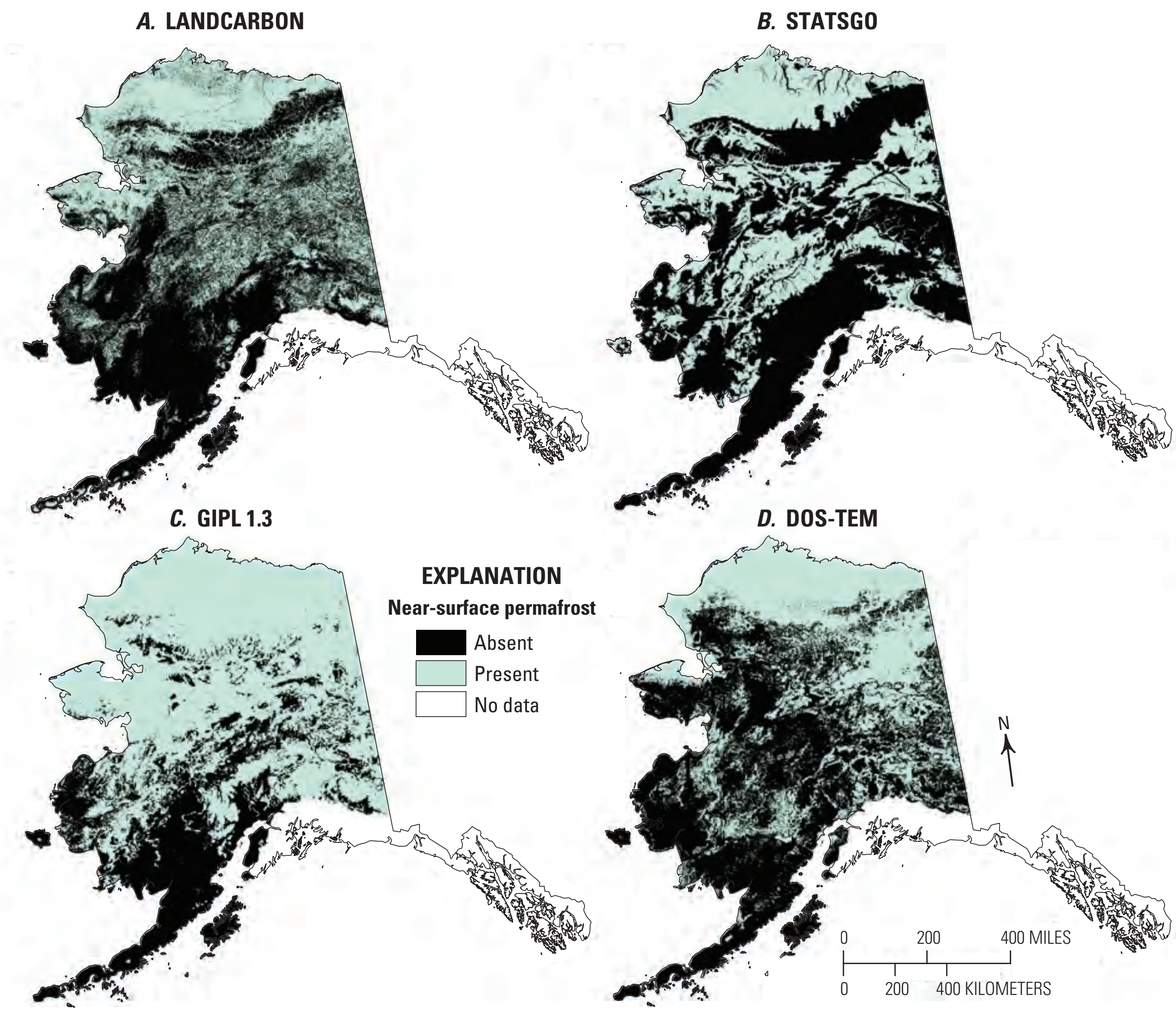

Figure 3.2. Estimated presence or absence of near-surface (within 1 meter) permafrost for Alaska. *A*, Permafrost from LANDCARBON (Pastick and others, 2015). *B*, Permafrost derived from the state soil geographic database (STATSGO). *C*, Permafrost simulated by the Geophysical Institute Permafrost Laboratory version 1.3 transient model (GIPL 1.3). *D*, Permafrost simulated by the Dynamic Organic Soil version of the Terrestrial Ecosystem Model (DOS-TEM). Map estimates are not reported for the North Pacific LCC.

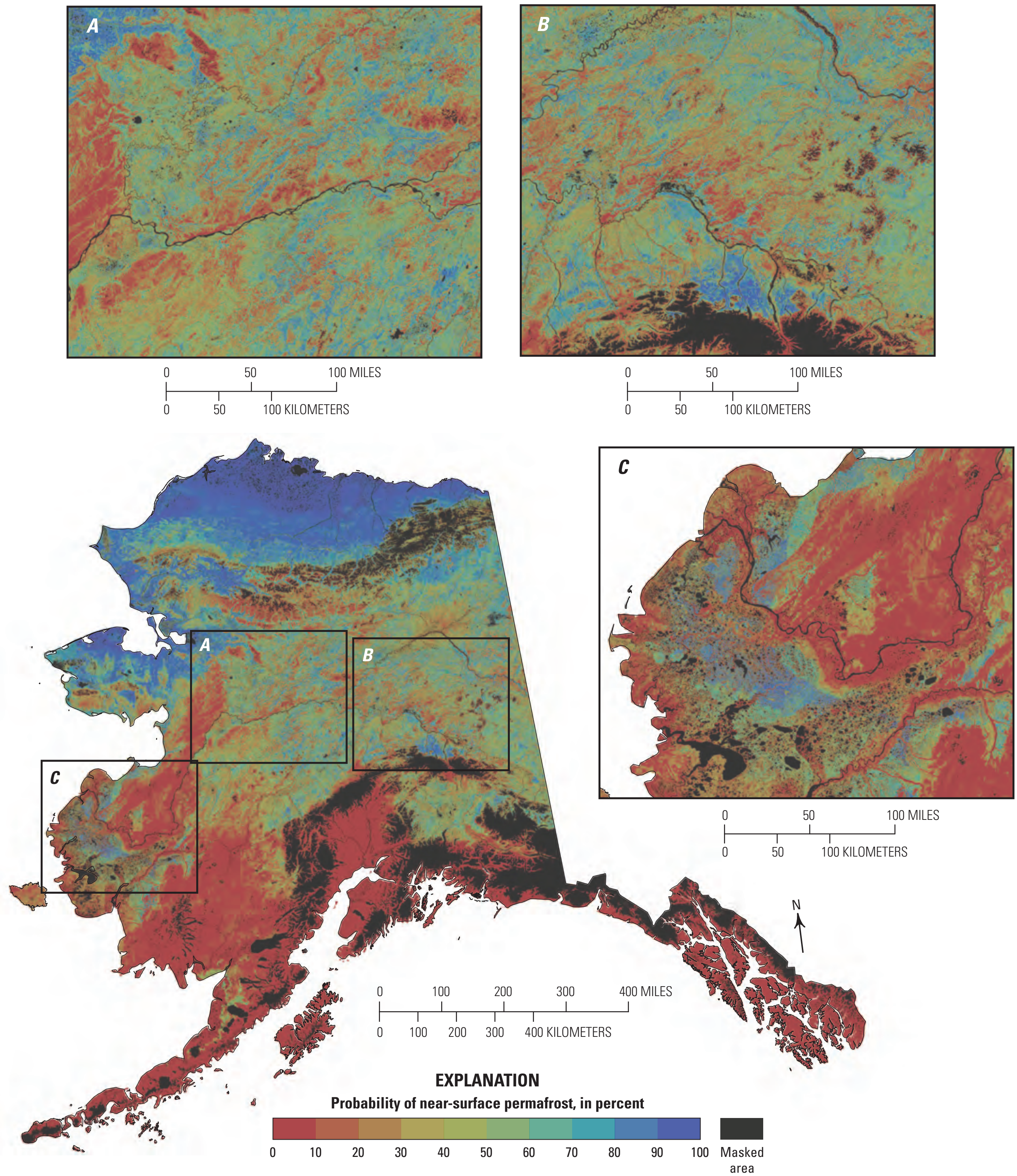

Figure 3.3. Probabilistic estimation of near-surface (within 1 meter) permafrost occurrence for the State of Alaska at 30-meter spatial resolution derived from LANDCARBON. Estimates were made using machine learning algorithms, field observations, remotely sensed or mapped imagery, and climatic data (Pastick and others, 2015).

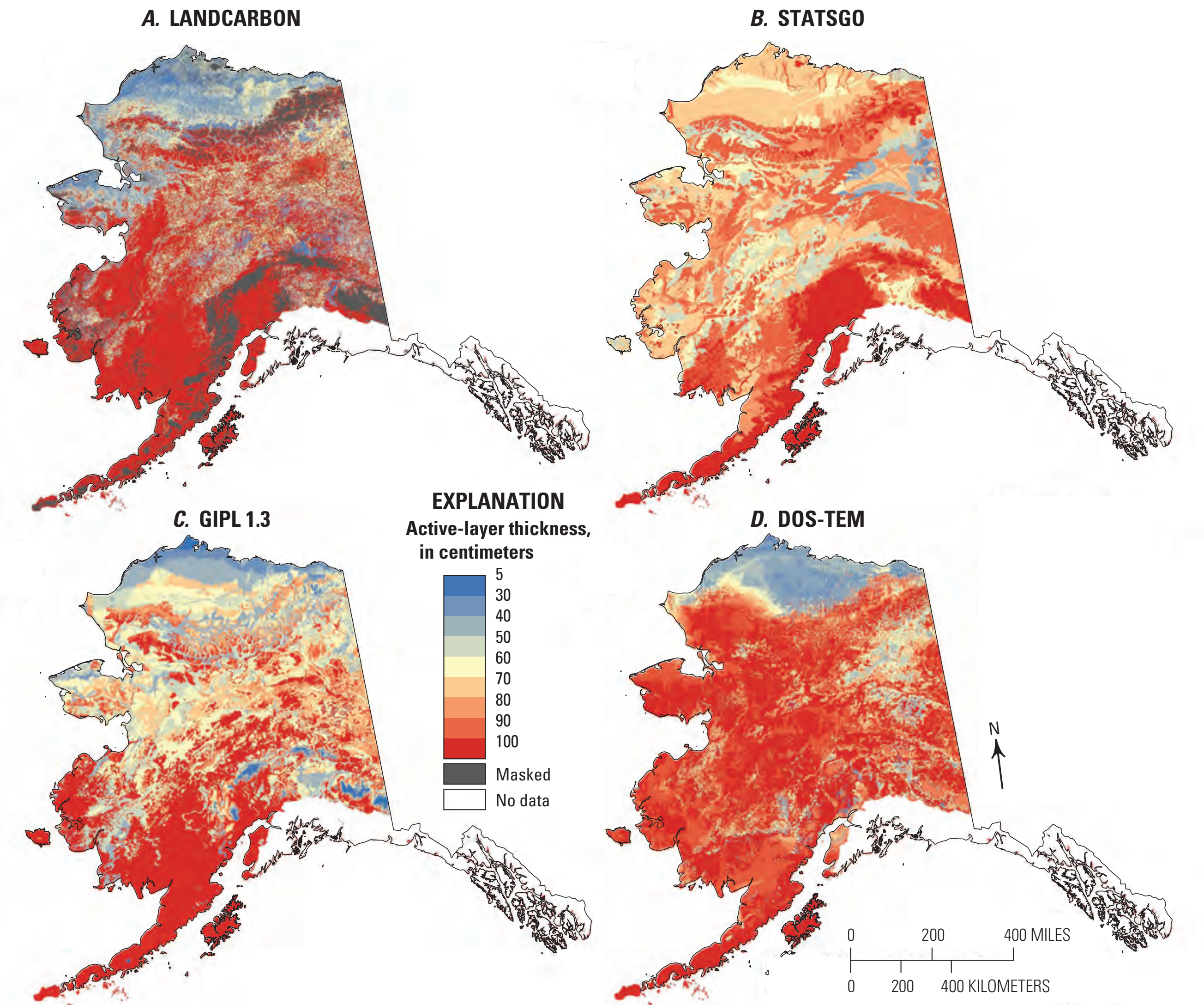

Figure 3.4. Active-layer thickness (ALT) estimates for Alaska. *A*, ALT derived from LANDCARBON (Pastick and others, 2015). *B*, ALT derived from the state soil geographic database (STATSGO). *C*, ALT simulated by the Geophysical Institute Permafrost Laboratory version 1.3 transient model (GIPL 1.3). *D*, ALT simulated by the Dynamic Organic Soil version of the Terrestrial Ecosystem Model (DOS-TEM). Map estimates are not reported for the North Pacific LCC. Areas where ALT was estimated to be greater than 1 meter were given a consistent value (dark red) because of differences in investigation depths and for direct comparison. ALT greater than 1 meter is dependent on site, soil, climate, and fire history.

depth of seasonal freezing and thaw by numerically solving one-dimensional nonlinear heat equations with phase change (Marchenko and others, 2008). Note that the spatial resolution (2-km pixels) of the GIPL 1.3 product is different than products developed in this study. Furthermore, predictions of seasonal frost or thaw depths greater than 1 m made by GIPL 1.3, for the years 2000 to 2009, were recoded to 101 cm for direct comparison with estimates of NSP and ALT produced for this study (figs. 3.2*C*, 3.4*C*).

The DOS-TEM permafrost products were produced from the historical simulations for Alaska at a 1-km resolution. In this process-based model, NSP and ALT were assessed based on soil temperature and soil moisture simulations over a 5-m-deep soil column. NSP is considered present when soil temperature at 1 m from the surface remained frozen for two consecutive years. Soil temperature and soil moisture in DOS-TEM are driven by climate, soil texture, and drainage conditions. The insulating properties of the snow cover, moss, and organic layers are also reproduced in the model. Soil moisture is also affected by water uptake from vegetation and runoff. NSP and ALT distributions were estimated by averaging annual estimates from 1950 to 1960, which is temporally inconsistent from other products but the only TEM outputs available for comparison at the time of analyses (figs. 3.2*D*, 3.4*D*).

3.4.3. Organic-Layer Thickness

For the multiple product analysis of this report, the available organic soil products included three new maps and one existing map (table 3.3).

The LANDCARBON OLT products were developed for this assessment using decision tree classifications to spatially extend field observations of soil organic-layer thickness (OLT; excluding buried O horizons) throughout Alaska. This approach made use of approximately 3,500 field observations and topographical, climatic, and remotely sensed geospatial data to map the presence or absence of organic soils (that is, OLT ≥ 40 cm = organic soil present; OLT < 40 cm = organic soil absent) (fig. 3.5*A*). The 40-cm depth interval was chosen because it coincides with Soil Taxonomy (Soil Survey Staff, 1999) nomenclature for organic soils (that is, Histosol or Histel) that are commonly associated with peatlands. Field observations were primarily collected by the National Resource Conservation Service, ABR, Inc., and the USGS (Pastick, Rigge, and others, 2014). Topography (that is, slope, soil-wetness proxies), length of growing season, and remotely sensed or mapped data (that is, land cover, vegetation indices) were identified to be the most important factors in estimating organic soil distributions in Alaska. Cross-validation accuracy assessments indicated that the map of the presence or absence of organic soil had an overall accuracy of 71 percent (95-percent CI: 69.5, 73.2). Readers are referred to Pastick, Rigge, and others (2014) for a thorough discussion on digital mapping of organic soils in Alaska.

The STATSGO OLT product was developed by evaluating the textural component of the horizons from the surface to 152-cm depth. For the STATSGO OLT, each horizon is labeled as organic or not organic, and the thickness of organic horizons is summed to create a component-level variable. This is weighted by the component percentage to give an average OLT at the map unit level. If an organic layer is not present, the thickness will be recorded as zero, and this will be included in the weighted average. The thicknesses of the organic layers in the 0- to 152-cm-depth zone were summed for each component, and a weighted average (with component percentage as the weight) was computed. If the average was more than 40 cm, then the map unit was labeled as "OLT ≥ 40 cm" in figure 3.5*B*.

The NCSCDv2 OLT product assigns soil type frequencies to a compilation of soil polygon maps for the whole circumpolar region, but does not include a large portion of southeastern Alaska (Hugelius and others, 2013). Although available at approximately 1-km resolution, the polygon representation of soils is considerably coarser than that represented by other products in this study. The data used for comparison are frequency of Histel occurrence estimates, which are comparable to organic soil products developed for this study.

The DOS-TEM OLT product (fig. 3.5*C*) provides estimates of OLT as a function of SOC content in the organic layer. The dynamic organic soil module of DOS-TEM simulates post-fire re-accumulation of the organic layer as dead organic soil horizons accumulate above the mineral horizons with post-fire vegetation succession. DOS-TEM estimates of organic soils are provided at a 1-km resolution for the entire State, excluding the North Pacific LCC, and represent averaged model estimates from 1950 to 1960.

3.4.4. Soil Susceptibility to Climate Change

The permafrost, soil carbon, and organic soils summaries presented in this study can yield useful information about the potential effects of climate change, particularly when multiple ecotype attributes are combined. For this purpose, ecotype means and measures of uncertainty from the multiple sources of relative frequency of NSP, relative frequency of organic soils, and mean ALT were combined in a database with ecotype estimates of frozen carbon and total organic carbon in the depth range of 0 to 1 m. This synthesis effort was constrained to the soil parameters presented in this chapter to focus on relative susceptibility. Important susceptibility

Table 3.3. Summary of spatial products and process-based model evaluated for soil organic-layer thickness in this assessment.

[LANDCARBON, data product developed for this assessment; STATSGO, state soil geographic database; NCSCDv2, Northern Circumpolar Soil Carbon Database version 2; DOS-TEM, Dynamic Organic Soil version of the Terrestrial Ecosystem Model; —, not applicable]

Product name	Extent	Resolution	Method	Number of observations	Reference
LANDCARBON	Alaska	30 meter	Machine learning	~3,500	This report
STATSGO	Alaska	1 kilometer	Means extrapolated to polygons	—	This report
NCSCDv2	Boreal and arctic Alaska	Polygons	Means extrapolated to polygons	—	Hugelius and others (2013)
DOS-TEM	Alaska (excluding the North Pacific Landscape Conservation Cooperative)	1 kilometer	Process-based model	—	This report

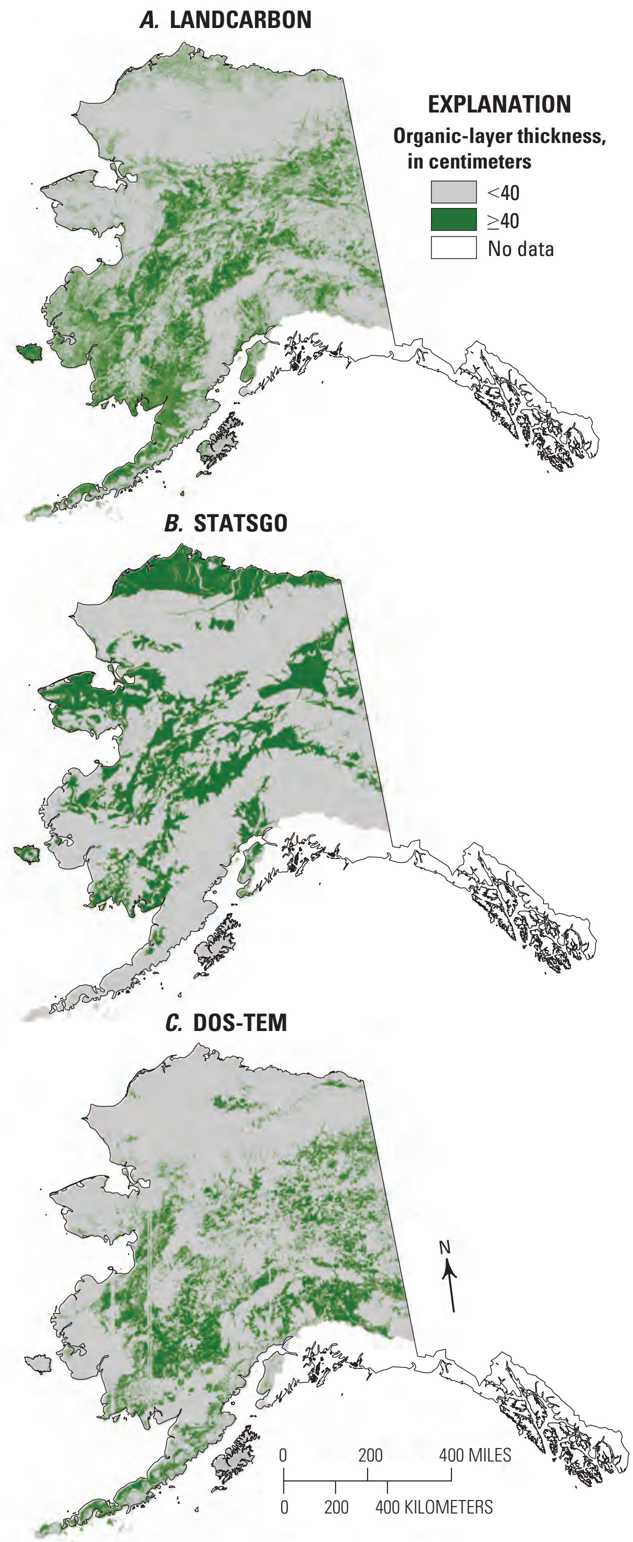

Figure 3.5. Organic-layer thickness (OLT) estimates for Alaska. *A*, OLT derived from LANDCARBON (Pastick and others, 2015). *B*, OLT derived from the state soil geographic database (STATSGO). *C*, OLT simulated by the Dynamic Organic Soil version of the Terrestrial Ecosystem Model (DOS-TEM). DOS-TEM model estimates are not reported for the North Pacific LCC.

drivers, such as fire return interval and temperature, were not included and are included in other chapters. Six ecologically driven criteria were constructed with each criterion having its separate binary response (0=false and 1=true). Generally, the first condition in these criteria sought to capture one-third of the ecotypes and subsequent condition constraints with other variables sought to identify the top two to six ecotypes. The six criteria consisted of:

1. Thicker soil organic layers provide protecting insulation for NSP (Johnson and others, 2013). To identify areas which may be prone to permafrost degradation, we selected ecotypes with a higher chance of having thin organic soils (relative frequency of organic soils less than 20 percent) and with permafrost close to the surface (relative frequency of NSP greater than 50 percent).

2. Criterion 2 is a subset of criterion 1. In the sensitive areas where criterion 1 is focused (NSP and thin organic soils), high uncertainty and wide variations in ecotype ALT would affect current and future hydrology and greenhouse-gas emissions significantly. Given the significance of future permafrost degradation related to greenhouse gases (Schaefer and others, 2011) and changing permafrost's potential effects on hydrologic flows (Walvoord and others, 2012), ecotypes with high uncertainties of ALT could experience greater-than-expected permafrost degradation and increased ecosystem respiration. We refined criterion 1 to NSP with thin organic soils, with an additional requirement of a relatively high uncertainty of ALT (inter-product ecotype ALT MAD greater than 6 cm).

3. Moderate to high OLTs could be particularly susceptible to wildfire (Kasischke and Johnstone, 2005). The fire susceptibility criterion was defined here as an organic soil relative frequency greater than 20 percent and not to include land-cover types with low flammability (deciduous forests and wetlands).

4. Thermokarst land surfaces often occur in regions with near-surface, ice-rich permafrost and moderate to thick soil organic layers. This criterion consisted of ecotypes with relative frequency of organic soils greater than 20 percent, with the relative frequency of NSP greater than 50 percent, and with ALT less than 76 cm.

5. Areas with high carbon stocks in the organic layer and in the mineral layers in the top 1 to 1.5 m represent potential hot spots for massive carbon loss owing to warming, fires, and accelerated soil respiration and greenhouse-gas emissions (Schuur and others, 2008). This criterion was simply ecotypes with inter-product total profile soil carbon ecotype means greater than 40 kgC/m^2.

6. Criterion 6 is a subset of criterion 5. Permafrost can contain significant organic carbon. If this permafrost carbon is close to the soil surface, it may be susceptible to thaw and be available for decomposition (Schuur and others, 2008). As permafrost thaws, the active layer thickens. This criterion consisted of ecotypes where the frozen carbon was greater than 10 kgC/m^2 and the total carbon in the top 1 to 1.5 m of soil was more than 40 kgC/m^2.

These six diverse criteria were focused on known or expected dynamics of permafrost, carbon, and the organic layer in boreal and arctic systems. To summarize overall factors, a susceptibility score, or ranking, was computed by summing all of the binary criteria variables and using area as a tie-breaker.

3.5. Results and Discussion

3.5.1. Comparison of Soil Organic Carbon Estimates

Generally, SOC densities of the three soil product properties (total profile, surface organic layer, and 1-m mineral layer; fig. 3.6) had the largest range of estimated values as well as high uncertainty in the Arctic LCC. Additional field data collection in these regions could reduce uncertainty in these important arctic systems. STATSGO SOC estimates appeared to be consistently low and MISHRA estimates tended to be consistently high in nearly all the ecotypes, but particularly so in the Arctic LCC. DOS-TEM estimates generally agreed with mean organic carbon estimates for each ecotype, falling within the range of estimates for 78 percent of the major ecotypes. However, in some forests of the Northwest Boreal LCC North, DOS-TEM SOC estimates were either near or below the lower data range of the SOC ecotype ranges. DOS-TEM estimates were only substantially above the range of other SOC estimates in the Northwest Boreal LCC South upland heath tundra.

The SOC density of the surface organic layer had high magnitudes and narrow data ranges (less uncertainty) in the deciduous forest, black spruce forest, and white spruce forest in the Northwest Boreal LCC North lowlands. DOS-TEM estimates of surface organic-layer carbon were substantially lower in these ecotypes and also in the Western Alaska LCC lowland shrub tundra. Thirty percent of all the ecotypes had DOS-TEM estimates within the soil organic-layer prediction range. The mean surface organic-layer carbon among all ecosystem types accounted for about 30 percent of the mean total soil carbon.

Only two spatial estimates (STATSGO and JOHNSON) of carbon in the mineral soil layer down to a depth of 1 m below the surface organic layer were available for comparison with estimates from DOS-TEM. The highest values for both spatial estimates occurred in the Arctic LCC. Disagreement between the two estimates and DOS-TEM estimates indicated possible overestimation by DOS-TEM in the Northwest Boreal LCC South upland heath tundra and the Western Alaska LCC.

In terms of total soil carbon storage (in PgC) by LCC region, DOS-TEM SOC estimates were close to the mean and within the range of four products in the Arctic and Western Alaska LCCs (table 3.4). However, DOS-TEM estimates were 40 percent lower than the mean of all the products in the Northwest Boreal LCC North and 94 percent higher than the mean in the Northwest Boreal LCC South. These general differences were true even when compared to the JOHNSON SOC product with exactly comparable SOC by depth. Despite these differences in distribution of SOC pools by LCC region, when all the LCC regions were summed, DOS-TEM estimates were only 2 percent higher than the mean.

Table 3.4. Comparisons of soil organic carbon storage for each of the Landscape Conservation Cooperative (LCC) regions in Alaska (except the North Pacific LCC) estimated using spatial products and DOS-TEM outputs.

[PgC, petagram of carbon; STATSGO, state soil geographic database; NCSCDv2, Northern Circumpolar Soil Carbon Database version 2; CAVM, Circumpolar Arctic Vegetation Map; DOS-TEM, Dynamic Organic Soil version of the Terrestrial Ecosystem Model; OL, surface organic layer; MIN1m, mineral soil to 1-meter depth below the bottom of the surface organic layer; OL+MIN1m, the sum of OL and MIN1m; —, not applicable]

Product name	Depth	Soil organic carbon (PgC)				
		Arctic LCC	Western Alaska LCC	Northwest Boreal LCC North	Northwest Boreal LCC South	Total or mean
JOHNSON	OL+MIN1m	13.6	11.3	14.4	4.4	43.7
STATSGO	OL+MIN1m	6.2	9.8	12.5	2.7	31.2
MISHRA	“whole profile”	20.7	22.8	22.6	6.1	72.1
NCSCDv2	0–152 centimeters	11.6	8.6	10.9	2.1	33.2
Mean	—	**13.0**	**13.1**	**15.1**	**3.8**	**45.2**
DOS-TEM	OL+MIN1m	12.4	17.3	9.0	7.4	46.1
MAD[1]	—	**0.6**	**4.2**	**6.1**	**3.6**	**0.9**
% Diff[2]	—	**4.8**	**31.8**	**40.4**	**93.5**	**2.1**

[1]Mean Absolute Difference (MAD) = |DOS-TEM − Mean|

[2]% Diff = (MAD / Mean) × 100

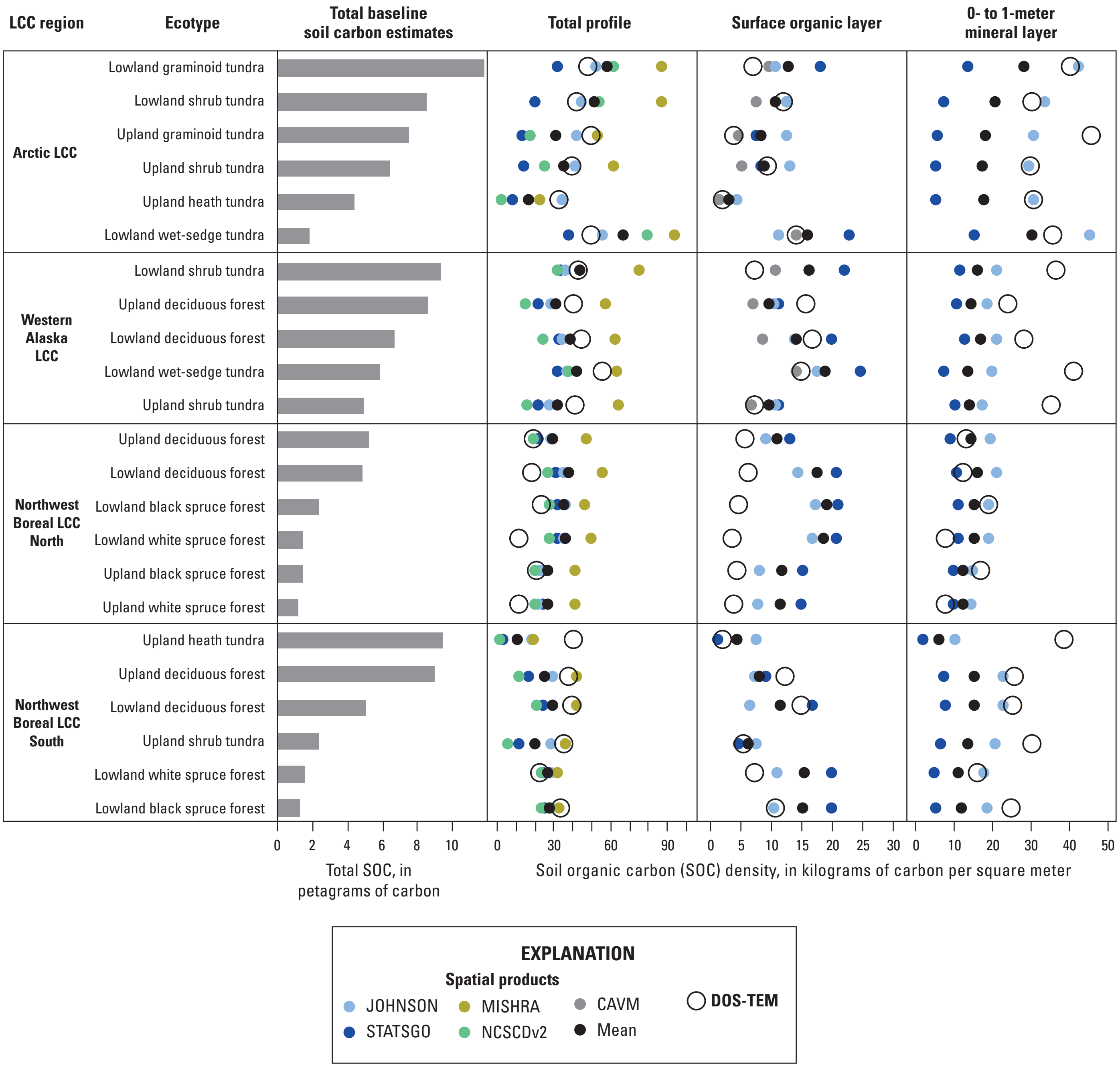

Figure 3.6. Soil organic carbon (SOC) characterization for the largest (in terms of SOC, in petagrams of carbon, PgC) five or six ecotype classes in each Landscape Conservation Cooperative (LCC) region. Total baseline SOC estimates simulated by the Dynamic Organic Soil version of the Terrestrial Ecosystem Model (DOS-TEM). Total profile SOC density is the sum of the surface organic layer and the 0- to 1-meter mineral layer for all estimates. "Mean" refers to the mean of all spatial products: JOHNSON, SOC from Johnson and others (2011); STATSGO, SOC from the state soil geographic database; MISHRA, SOC from Mishra and Riley (2012); NCSCDv2, SOC from the Northern Circumpolar Soil Carbon Database version 2; and CAVM, SOC from the Circumpolar Arctic Vegetation Map. Estimates are not reported for the North Pacific LCC.

The lower estimate of SOC in the organic layer provided by DOS-TEM compared with the other models in the Northwest Boreal LCC North may be attributed to the effect of fire simulated in the model. The version of DOS-TEM used for the present assessment has been designed to reproduce the effect of fire on nitrogen and carbon cycles in the soil and vegetation and on the soil environment, including the re-accumulation of the organic layer after a fire (Yi and others, 2009, 2010). Furthermore, a fire severity model has also been implemented in order to reproduce the spatial and temporal variability of fire severity on the organic layer (Genet and others, 2013). During the model spin-up, the fire regime was simulated by a constant fire return interval computed from the historical fire records for Alaska. Because the fire return interval is shortest in the Northwest Boreal LCC North, more organic layer is burned and less SOC accumulates.

The higher SOC in the mineral layers observed in DOS-TEM compared with the JOHNSON SOC and STATSGO SOC estimates in the Western Alaska LCC might be related to the underestimation of the effect of the warmer climate on soil decomposition processes in this region. However, given that there are only two products available for comparison and the low sample density in the Western Alaska LCC, there is less confidence that the mineral SOC product is a reliable reference.

3.5.2. Comparison of Permafrost Estimates

NSP estimates (fig. 3.2) were summarized as relative frequency in percent by LCC region and DOS-TEM land-cover type in tables 3.5 and 3.6. According to empirically or numerically derived NSP products, NSP was estimated to underlie a large portion of Alaska with a wide range of estimates (36 to 67 percent). The mean NSP frequency of DOS-TEM outputs (44 percent) falls within this range. On average, NSP distributions followed north-to-south temperature gradients as expected, with the largest NSP frequencies in the Arctic LCC (73 percent), followed by the Northwest Boreal LCC North (55 percent), and Western Alaska LCC and Northwest Boreal LCC South (30 percent each). DOS-TEM outputs were consistently within the range of other model outputs and were (on average) within 3 percent of the mean of other products (table 3.5).

A mean estimate (excluding DOS-TEM) of NSP frequencies varied nearly seventyfold between DOS-TEM land-cover types (table 3.6). Graminoid tundra had the highest mean product frequency of being underlain by NSP (73 percent), followed by shrub tundra (60 percent), black spruce forest (53 percent), white spruce forest (52 percent), deciduous forest (40 percent), wet-sedge tundra (34 percent), nonvegetated areas (31 percent), heath tundra (29 percent), and maritime classes (1 percent). Vegetation succession can serve as a positive feedback to permafrost systems, where increasing components of soil organics and moisture can provide insulation to permafrost, consistent with higher NSP frequencies in white and black spruce forests (late successional stages) compared with deciduous forests (early successional stages). Furthermore, DOS-TEM outputs were significantly correlated (p-value <0.05) with mean product NSP frequencies when stratified by LCC region (coefficient of determination, $R^2=0.86$; n=5) or land-cover type ($R^2=0.69$; n=9). Empirically derived NSP maps (that is, STATSGO and LANDCARBON) were significantly correlated when comparing NSP estimates stratified by LCC region ($R^2=0.82$; n=5) and DOS-TEM land-cover type ($R^2=0.63$; n=9). DOS-TEM outputs best correlated with the GIPL 1.3 map when examining mean NSP estimates stratified by LCC region ($R^2=0.98$; n=5) and DOS-TEM land-cover type ($R^2=0.72$; n=9). Large differences between model outputs are most evident for areas estimated to have little to no vegetation. Mean product NSP frequencies indicate that lowland areas are more frequently underlain by NSP than uplands in Alaska (57 percent versus 36 percent), consistent with trends in DOS-TEM outputs (49 percent versus 41 percent). Large differences between mean NSP frequencies in uplands suggest that estimates of NSP distributions are relatively more uncertain for upland than lowland ecosystems, coinciding with large differences in NSP estimates for areas with little to no vegetation. A portion of these differences can be attributed to how models handled glaciated areas.

Finer scale comparisons were also made where NSP estimates were stratified by ecotype in each LCC region (excluding the North Pacific LCC; fig. 3.7). Empirically derived NSP maps were in global accordance with one another and with DOS-TEM outputs when mean frequency estimates are stratified by ecotype. For instance, the empirically derived NSP maps (that is, STATSGO and LANDCARBON) were significantly (p-value <0.05) correlated when estimates were stratified by ecotype in each LCC region ($R^2=0.83$; n=23). Additionally, DOS-TEM outputs were significantly correlated ($R^2=0.67$; n=23) with mean product NSP frequencies stratified by ecotype. Furthermore, in 87 percent of the major ecotype classes the DOS-TEM output is within the range of other products, whereas three of the DOS-TEM outputs were outside the range. The three low DOS-TEM outputs were within upland and lowland shrub tundra in the Western Alaska LCC and lowland deciduous forests in the Northwest Boreal LCC North. These significant differences could have a large effect on future model simulations because these ecotypes account for a substantial portion of Western Alaska LCC (33 percent) and Northwest Boreal LCC North (25 percent). The lower DOS-TEM estimate of NSP distribution compared with the other models in interior Alaska (Northwest Boreal LCC North) might be related to the lower estimate of OLT related to the effect of fire activity and high fire return interval in the region (see section 2.4.2.). With a thinner organic layer, the soil is less insulated from large variability of air temperature, especially high summer temperature. As a consequence, the annual mean of soil temperature increases, thawing permafrost and increasing ALT.

Table 3.5. Comparisons of the frequency of near-surface (within 1 meter) permafrost, mean active-layer thickness, and frequency of organic soils for Landscape Conservation Cooperative (LCC) regions in Alaska (except the North Pacific LCC) estimated using spatial products and DOS-TEM outputs.

[Organic soils are defined here as those soils with a surface organic epipedon that is greater than or equal to 40 centimeters. LANDCARBON, data product developed for this assessment; STATSGO, state soil geographic database; GIPL 1.3, Geophysical Institute Permafrost Laboratory version 1.3 transient model; DOS-TEM, Dynamic Organic Soil version of the Terrestrial Ecosystem Model; NCSCDv2, Northern Circumpolar Soil Carbon Database version 2]

Product name	Landscape Conservation Cooperative region				
	Arctic LCC	Western Alaska LCC	Northwest Boreal LCC North	Northwest Boreal LCC South	Mean
Frequency of near-surface permafrost (percent)					
LANDCARBON	66	21	44	22	38
STATSGO	56	28	49	11	36
GIPL 1.3	97	41	72	57	67
Mean	**73**	**30**	**55**	**30**	**47**
DOS-TEM	73	22	45	38	44
MAD[1]	**0**	**8**	**10**	**8**	**3**
% Diff[2]	**0**	**26**	**19**	**25**	**5**
Mean active-layer thickness (centimeter)					
LANDCARBON	59.51	88.94	81.14	91.43	80.26
STATSGO	79.71	85.08	76.68	95.60	84.27
GIPL 1.3	60.88	85.55	78.49	78.34	75.81
Mean	**66.70**	**86.52**	**78.77**	**88.45**	**80.11**
DOS-TEM	72.80	95.86	88.63	87.46	86.19
MAD[1]	**6.10**	**9.34**	**9.86**	**0.99**	**6.08**
% Diff[2]	**9.14**	**10.79**	**12.51**	**1.12**	**7.58**
Frequency of organic soils (percent)					
LANDCARBON	6	31	35	19	24
STATSGO	27	25	37	9	30
NCSCDv2	4	13	7	2	8
Mean	**12**	**23**	**26**	**10**	**21**
DOS-TEM	3	24	26	38	18
MAD[1]	**10**	**1**	**1**	**29**	**3**
% Diff[2]	**77**	**4**	**2**	**298**	**15**

[1]Mean Absolute Difference (MAD) = |DOS-TEM − Mean|

[2]% Diff = (MAD / Mean) × 100

Table 3.6. Comparisons of the frequency of near-surface (within 1 meter) permafrost, mean active-layer thickness, and frequency of organic soils by DOS-TEM land-cover type estimated using spatial products and DOS-TEM outputs.

[Areas estimated to have active-layer thicknesses greater than 1 meter were given a value of 101 centimeters for direct comparison and to account for differences in investigation depths. Organic soils are defined here as those soils with a surface organic epipedon that is greater than or equal to 40 centimeters. LANDCARBON, data product developed for this assessment; STATSGO, state soil geographic database; GIPL 1.3, Geophysical Institute Permafrost Laboratory version 1.3 transient model; DOS-TEM, Dynamic Organic Soil version of the Terrestrial Ecosystem Model; NCSCDv2, Northern Circumpolar Soil Carbon Database version 2]

Product name	Land-cover type							
	Black spruce forest	**White spruce forest**	**Deciduous forest**	**Shrub tundra**	**Graminoid tundra**	**Wet-sedge tundra**	**Heath tundra**	**Non-vegetated**
Frequency of near-surface permafrost (percent)								
LANDCARBON	40	38	30	54	70	27	7	44
STATSGO	52	48	35	55	57	27	1	8
GIPL 1.3	66	70	55	71	93	49	77	40
Mean	**53**	**52**	**40**	**60**	**73**	**34**	**29**	**31**
DOS-TEM	49	52	36	47	62	59	40	20
MAD[1]	**4**	**0**	**4**	**13**	**11**	**24**	**11**	**11**
% Diff[2]	**7**	**1**	**9**	**22**	**15**	**71**	**39**	**35**
Mean active-layer thickness (centimeter)								
LANDCARBON	84.1	85.0	88.6	67.1	60.3	44.3	101.0	92.0
STATSGO	76.5	78.2	83.5	79.3	78.9	81.5	97.9	96.1
GIPL 1.3	80.2	77.9	83.3	72.5	59.7	39.6	101.0	85.8
Mean	**80.3**	**80.3**	**85.1**	**72.9**	**66.3**	**55.1**	**100.0**	**91.3**
DOS-TEM	87.9	85.9	90.4	84.2	76.0	74.9	90.9	91.2
MAD[1]	**7.7**	**5.6**	**5.2**	**11.3**	**9.7**	**19.8**	**9.0**	**0.1**
% Diff[2]	**9.5**	**6.9**	**6.2**	**15.5**	**14.7**	**35.9**	**9.0**	**0.1**
Frequency of organic soils (percent)								
LANDCARBON	34	32	36	16	10	48	1	7
STATSGO	40	36	27	22	38	39	1	17
NCSCDv2	8	8	5	6	6	28	0	8
Mean	**27**	**25**	**23**	**15**	**18**	**38**	**1**	**11**
DOS-TEM	25	22	43	7	1	4	0	8
MAD[1]	**2**	**3**	**21**	**7**	**17**	**35**	**0**	**2**
% Diff[2]	**8**	**13**	**91**	**49**	**95**	**90**	**62**	**21**

[1]Mean Absolute Difference (MAD) = |DOS-TEM − Mean|

[2]% Diff = (MAD / Mean) × 100

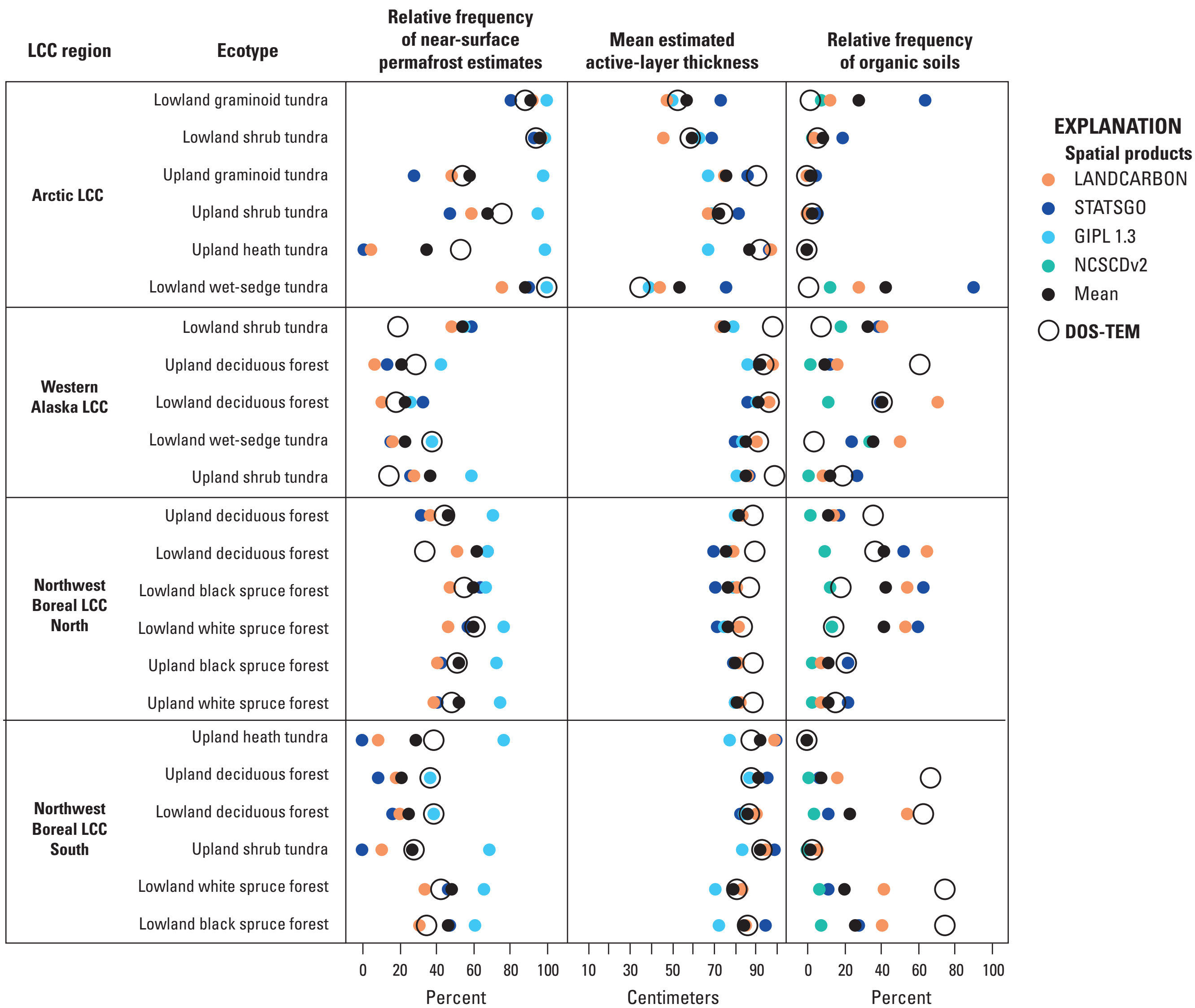

Figure 3.7. Permafrost and organic soil characterization for the largest (in terms of soil organic carbon, in petagrams of carbon) five or six ecotype classes in each Landscape Conservation Cooperative (LCC) region. Areas estimated to have active-layer thicknesses greater than 1 meter were given a value of 101 centimeters for direct comparison and to account for differences in investigation depths. Organic soils are defined here as those soils with a surface organic epipedon that is greater than or equal to 40 centimeters. "Mean" refers to the mean of all relevant estimates except the Dynamic Organic Soil version of the Terrestrial Ecosystem Model (DOS-TEM): LANDCARBON, permafrost and organic soil data from Pastick and others (2015); STATSGO, permafrost and organic soil data from the state soil geographic database; GIPL 1.3, permafrost data from the Geophysical Institute Permafrost Laboratory version 1.3 transient model; and NCSCDv2, organic soil data from the Northern Circumpolar Soil Carbon Database version 2.

Spatial predictions of ALT (fig. 3.4) were also summarized by LCC region and DOS-TEM land-cover type in tables 3.5 and 3.6. Areas where the ALT was estimated to be greater than 1 m were given a consistent value (101 cm) because of differences in investigation depths and for a direct comparison of ALT products. Empirically or numerically derived ALT estimates had a mean ALT of 80 cm in Alaska (excluding the North Pacific LCC), with a range of 76 to 84 cm between estimates (table 3.5). The mean ALT estimate of the DOS-TEM output (86 cm) was slightly outside the range of other products, but within the range of uncertainty between other products (that is, MAD from product averages was 6 cm). The mean product ALT was thinnest in the Arctic LCC (67 cm), followed by the Northwest Boreal LCC North (79 cm), Western Alaska LCC (87 cm), and Northwest Boreal LCC South (88 cm). The mean ALT estimates of the DOS-TEM model were generally higher than other estimates. Furthermore, there was no significant correlation between DOS-TEM and mean product ALT estimates when stratified by LCC region. It is important to note, however, that there were significant correlations between mean ALT estimates of DOS-TEM, GIPL 1.3, and LANDCARBON when stratified by LCC region ($R^2 > 0.75$; n = 5). The lack of correlation between the mean product and DOS-TEM estimates was due to higher estimates of ALT in the STATSGO product for the Arctic LCC, which drives up the mean of other products. Higher Arctic LCC ALT estimates in the STATSGO product may stem from the fact that a frozen soil horizon was recorded in the database only if ice lenses were visible, not using a temperature criterion as in the definition of permafrost. Furthermore, there was no temporal constraint on those observations used during the creation of the STATSGO-derived ALT map.

Mean product ALT estimates varied approximately twofold between DOS-TEM land-cover types with no significant correlation to mean product NSP frequency estimates (table 3.6). Wet-sedge tundra had the lowest mean product ALT (55 cm), followed by graminoid tundra (66 cm), shrub tundra (73 cm), black and white spruce forests (80 cm each), deciduous forest (85 cm), nonvegetated areas (91 cm), heath tundra (100 cm), and maritime vegetation (>100 cm). DOS-TEM ALT outputs were significantly correlated with the mean ALT of other products when stratified by land-cover type ($R^2 = 0.87$; n = 9), despite 67 percent of the DOS-TEM outputs falling outside of the range of other ALT products. The largest differences between DOS-TEM output and the mean of other product ALT outputs were for tundra vegetation (that is, shrub, graminoid, wet-sedge, and heath tundra), which accounts for approximately 32 percent of Alaska, and where there is the largest range in other ALT estimates.

ALT estimates were also stratified and averaged by ecotype in each LCC region (excluding the North Pacific LCC; fig. 3.7). Empirically or numerically derived ALT maps were generally in global accordance with one another and with DOS-TEM outputs. For instance, the ALT maps produced by Pastick and others (2015) (LANDCARBON) and Marchenko and others (2008) (GIPL 1.3) were significantly correlated when ALT estimates are averaged by ecotype ($R^2 = 0.67$; n = 23). The DOS-TEM and GIPL 1.3 products had the highest correlation ($R^2 = 0.78$; n = 23) when comparing mean ALT estimates of each major ecotype, but DOS-TEM outputs were also significantly correlated ($R^2 = 0.73$; n = 23) with estimates made by Pastick and others (2015) (LANDCARBON). DOS-TEM outputs were significantly correlated with the mean ALT of other outputs ($R^2 = 0.73$; n = 23). Furthermore, in 48 percent of the ecotype classes, the DOS-TEM output was within the range of other products, whereas 12 of the DOS-TEM outputs were outside the range. It is important to note, however, that DOS-TEM ALT outputs were generally close to the intra-product means. For example, the rMAE or MAE of DOS-TEM outputs compared to the mean of all products was 8 percent or 7 cm, respectively. More than three-fourths of the high DOS-TEM outputs were for the Northwest Boreal LCC North and Western Alaska LCC, where permafrost is particularly vulnerable to climate warming (Shur and Jorgenson, 2007) and the ranges in mean ALT estimates are lowest. A spatially exhaustive comparison of continuous estimations of ALT could not be made because of differences in investigation depths.

3.5.3. Comparison of Soil Organic-Layer Estimates

Organic soil estimates were summarized by LCC region and DOS-TEM land-cover type in tables 3.5 and 3.6. According to observation-based OLT products, organic soils were estimated to underlie a fairly small portion of Alaska (excluding the North Pacific LCC) with a narrow range (8 to 30 percent) in frequency of occurrence. The mean organic soil frequency from DOS-TEM outputs (18 percent) falls within this range. On average, organic soils most frequently occurred in Northwest Boreal LCC North (26 percent), followed by the Western Alaska LCC (23 percent), the Arctic LCC (12 percent), and the Northwest Boreal LCC South (10 percent). At the LCC region level, DOS-TEM outputs were within the range of other products 60 percent of the time, with the largest difference occurring in the Northwest Boreal LCC South (table 3.5).

Wet-sedge tundra was estimated to be most frequently underlain by organic soils (38 percent; table 3.6), followed by black spruce forest (27 percent), white spruce forest (25 percent), deciduous forest (23 percent), graminoid tundra (18 percent), shrub tundra (15 percent), nonvegetated areas (11 percent), and heath tundra (1 percent). For a comparison, organic soil frequencies, as estimated in the LANDCARBON OLT product, varied considerably when stratified by NLCD class (wetlands and moss equal 97 to 100 percent; deciduous forest and dwarf shrub equal 0 to 8 percent) (Homer and others, 2007) but this land-cover dataset was also used for model development. DOS-TEM outputs were not significantly (p-value >0.18) correlated with the individual organic soil products or the mean of those products when estimates were averaged by land-cover type. However, 63 percent of DOS-TEM outputs were within the range of other product estimates, with only three outputs outside of the range of other products. Moreover, two of the three outlier DOS-TEM outputs were only slightly outside the range of other products, with the largest difference occurring in areas mapped as wet-sedge tundra, which represents a small fraction (4 percent) of the land cover of Alaska. Empirical model estimates (that is, STATSGO, LANDCARBON) were significantly correlated (R^2=0.53; n=9) when stratified by land-cover type.

Empirically derived organic soil maps are in global accordance with one another, when mean frequency estimates are stratified by ecotype in each LCC region, but less so in correspondence with DOS-TEM outputs (fig. 3.7). In 57 percent of the ecotype classes, the DOS-TEM output is within the range of other products, whereas 10 of the DOS-TEM outputs were outside the range. Moreover, DOS-TEM outputs were not significantly correlated (p-value=0.63; n=23) with the mean of other estimates when stratified by ecotype in each LCC region. Mean product organic soil frequencies indicate that lowlands are more frequently underlain by organic soils than uplands in Alaska (32 percent versus 8 percent), a pattern not seen in DOS-TEM outputs (19 percent versus 22 percent). The Western Alaska LCC and Northwest Boreal LCC South had the largest differences in organic soil estimates. Large differences in the range of model outputs suggest that the simulation of thick soil organic layers is difficult, partially owing to a large and complex set of biophysical factors (for example, soil moisture, disturbances) influencing organic soil distributions, and that DOS-TEM outputs of organic soils are currently highly uncertain.

3.5.4. Soil Susceptibility to Climate Change

The conceptual model of ecotype and soil susceptibility to climate change resulted in susceptibility scores ranging from a high of 4 to a low of 0. The map produced from this model can be seen in figure 3.8.

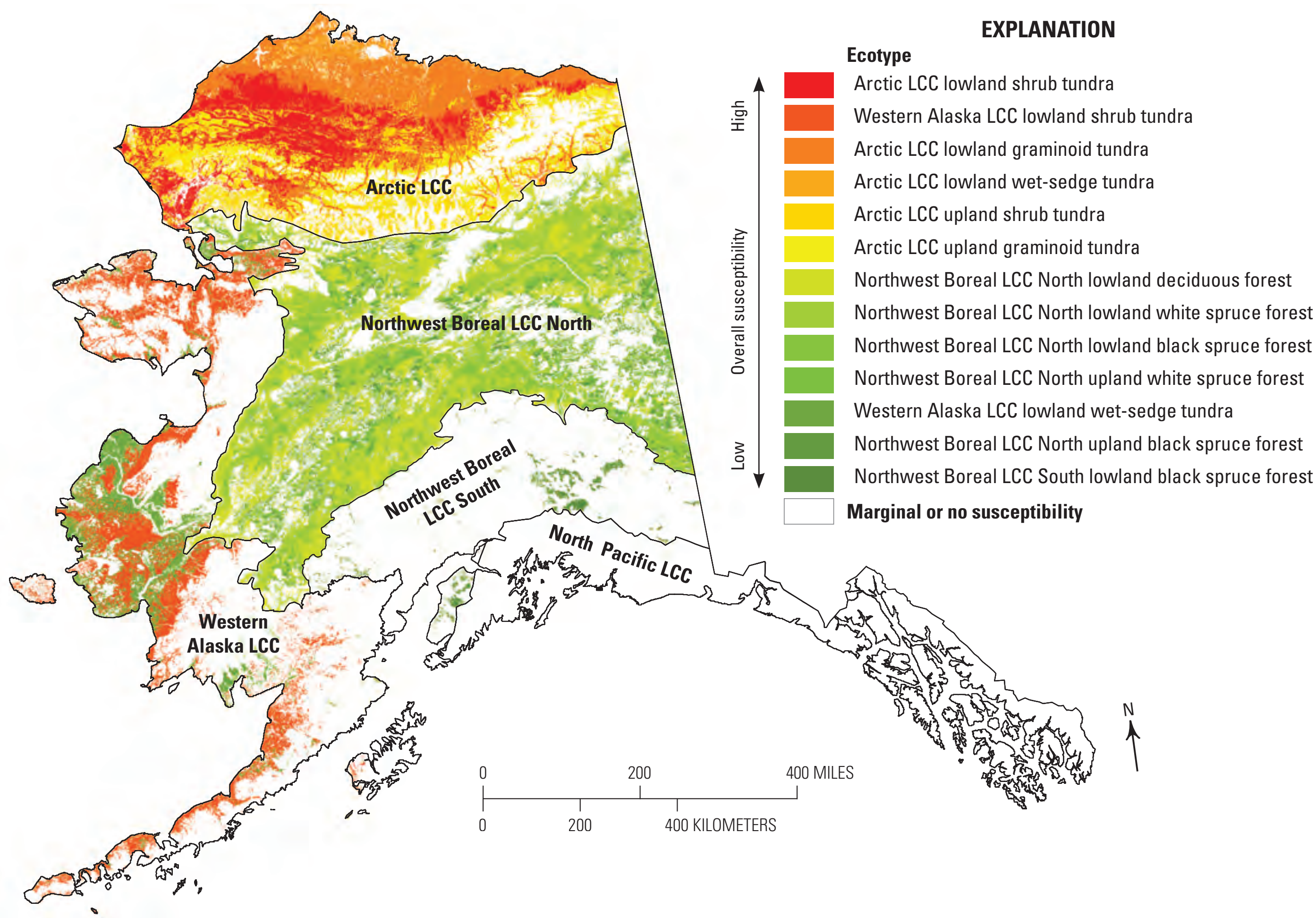

Figure 3.8. Overall soil susceptibility of major ecotypes in Alaska. Susceptibility was higher in ecotypes with greater respiration to the atmosphere, burning, and near-surface (within 1 meter) permafrost thaw.

The tundra ecotypes, Arctic LCC lowland graminoid, shrub, and wet-sedge tundra and Western Alaska LCC lowland shrub tundra, had the highest susceptibility scores. These four ecotypes had the highest total profile organic carbon product mean values, ranging from 44.5 to 66.9 kgC/m^2, and generally high frozen organic carbon and NSP (in three out of the four ecotypes). Arctic LCC upland shrub and graminoid tundra ecotypes had intermediate susceptibility scores, which were driven by susceptibility of NSP and high uncertainty. The persistence of the Arctic LCC within these top susceptibility scores is compounded by also having the highest carbon stocks and high uncertainty of SOC densities (fig. 3.6). The Arctic LCC graminoid and shrub tundra ecotypes had the highest ecotype frequencies of NSP. Western Alaska LCC lowland shrub tundra makes up 33 percent of the Western Alaska LCC and has the second highest susceptibility score. DOS-TEM outputs in this ecotype tended to underestimate organic-layer carbon, NSP, and organic soil relative frequencies and to overestimate ALT in this system with known permafrost vulnerabilities (Shur and Jorgenson, 2007). Extended ground surveys linked with mapping efforts in these susceptible ecotypes could reduce uncertainty and provide more accurate baseline datasets for assessing future changes and effects.

Ecotypes with low susceptibility scores (Northwest Boreal LCC North lowland black spruce, deciduous, and white spruce forests; Northwest Boreal LCC North upland black and white spruce forests; Northwest Boreal LCC South lowland black spruce forest; and Western Alaska LCC lowland wet-sedge tundra) further underscore the susceptibility of the Western Alaska LCC and Northwest Boreal LCC systems over the other remaining Alaska ecotypes, which had the lowest susceptibility scores. Low susceptibility scores of some Northwest Boreal LCC North ecotypes might have been higher if fire return interval or temperature were included in selected criteria. Given expected increases in fire severity and frequency (Barrett and others, 2011), this LCC region is important for understanding and forecasting future ecosystem responses. Organic-layer carbon estimates in Northwest Boreal LCC North lowland forest ecotypes had high magnitudes (fig. 3.6). DOS-TEM outputs for the Northwest Boreal LCC North tended to underestimate total profile carbon, soil organic-layer carbon, and mineral soil carbon (fig. 3.6) and to overestimate ALT (fig. 3.7).

Ecotypes with the lowest susceptibility scores were Arctic LCC upland heath tundra; Northwest Boreal LCC North upland deciduous forest; Northwest Boreal LCC South lowland deciduous and white spruce forests; Northwest Boreal LCC South upland deciduous forest and heath and shrub tundra; Western Alaska LCC lowland deciduous forest; and Western Alaska LCC upland deciduous forest and shrub tundra. Remarkably the separation of northern and southern components of the Northwest Boreal LCC was captured in susceptibility scores based solely on soil properties with no fire probability or climate inputs.

Despite the discrepancies between DOS-TEM outputs and those of other products highlighted above, in general DOS-TEM did a reasonable job capturing the spatial variations of important high-latitude soil attributes. The DOS-TEM total profile carbon, soil organic-layer carbon, ALT, and organic soil relative frequency were within the other product data range for 78 percent, 30 percent, 48 percent, and 57 percent of the ecotypes, respectively.

3.6. Conclusions

Soil carbon, permafrost, and organic soils are important components of high-latitude ecosystems. This chapter provides fundamental information as to the current state of knowledge of the distribution of these soil properties. This information will be of use for future field campaigns aimed at quantifying the resilience and vulnerability of high-latitude ecosystems to changes in climate and environment.

The synoptic comparison of estimates from multiple soil products with those of a process-based model (DOS-TEM) was useful to (1) identify areas of high soil attribute uncertainty, (2) identify areas of disagreement with the DOS-TEM estimates and mapped current conditions, (3) provide inter-product mean values which may be useful as baseline data for assessing and understanding future changes, and (4) identify areas of potential susceptibility to changing climates through inter-soil attribute combinations. These uncertainties could help prioritize field collections and studies on ecotypes with high uncertainties and high soil carbon stocks (particularly, the Arctic LCC). Discrepancies between DOS-TEM and other product estimates in Northwest Boreal LCC North SOC and ALT and upland versus lowland OLT will be useful for informing the uncertainty of future ecosystem responses to a changing climate made by DOS-TEM. The high soil susceptibility scores for the Arctic and Western Alaska LCCs may reinforce DOS-TEM future change projections.

This soil product spatial synthesis was constrained to the soil parameters presented in this chapter and was done at a relatively coarse resolution, at ecotype or coarser levels (LCC region or land-cover type). These coarser evaluation units helped to mitigate possible geolocation errors and to not penalize coarser polygon approaches. However, significant variations of permafrost and soil carbon related to adjacency to water and soil texture changes certainly occur within the broad ecotypes used in this study.

Refined and higher resolution products for Alaska can potentially be used to better insure that the current status of Alaska systems are captured in process-based models. This would improve confidence of future predictions made by these models.

3.7. References Cited

Amiro, B.D., Orchansky, A.L., Barr, A.G., Black, T.A., Chambers, S.D., Chapin, F.S., III, Goulden, M.L., Litvak, M., Liu, H.P., McCaughey, J.H., McMillan, A., and Randerson, J.T., 2006, The effect of post-fire stand age on the boreal forest energy balance: Agricultural and Forest Meteorology, v. 140, nos. 1–4, p. 45–50, http://dx.doi.org/10.1016/j.agrformet.2006.02.014.

Barrett, K., McGuire, A.D., Hoy, E.E., and Kasischke, E.S., 2011, Potential shifts in dominant forest cover in interior Alaska driven by variations in fire severity: Ecological Applications, v. 21, no. 7, p. 2380–2396, http://dx.doi.org/10.1890/10-0896.1.

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

Bliss, N.B., Waltman, S.W., West, L.T., Neale, Anne, and Mehaffey, Megan, 2014, Distribution of soil organic carbon in the conterminous United States, *in* Hartemink, A.E., and McSweeney, Kevin, eds., Soil carbon: Cham, Switzerland, Springer International Publishing, p. 85–93, http://dx.doi.org/10.1007/978-3-319-04084-4_9.

Chambers, S.D., and Chapin, F.S., III, 2002, Fire effects on surface-atmosphere energy exchange in Alaskan black spruce ecosystems; Implications for feedbacks to regional climate: Journal of Geophysical Research; Atmospheres, v. 107, no. D1, p. FFR 1–1 to FFR 1–17, http://dx.doi.org/10.1029/2001jd000530.

Chapin, F.S., III, McGuire, A.D., Ruess, R.W., Hollingsworth, T.N., Mack, M.C., Johnstone, J.F., Kasischke, E.S., Euskirchen, E.S., Jones, J.B., Jorgenson, M.T., Kielland, K., Kofinas, G.P., Turetsky, M.R., Yarie, J., Lloyd, A.H., and Taylor, D.L., 2010, Resilience of Alaska's boreal forest to climatic change: Canadian Journal of Forest Research, v. 40, no. 7, p. 1360–1370, http://dx.doi.org/10.1139/X10-074.

Clow, G.D., 2014, Temperature data acquired from the DOI/GTN–P Deep Borehole Array on the Arctic Slope of Alaska, 1973–2013: Earth System Science Data, v. 6, no. 1, p. 201–218, http://dx.doi.org/10.5194/essd-6-201-2014.

Euskirchen, E.S., McGuire, A.D., Chapin, F.S., III, and Rupp, T.S., 2010, The changing effects of Alaska's boreal forests on the climate system: Canadian Journal of Forest Research, v. 40, no. 7, p. 1336–1346, http://dx.doi.org/10.1139/X09-209.

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

Harden, J.W., Manies, K.L., Turetsky, M.R., and Neff, J.C., 2006, Effects of wildfire and permafrost on soil organic matter and soil climate in interior Alaska: Global Change Biology, v. 12, no. 12, p. 2391–2403, http://dx.doi.org/10.1111/j.1365-2486.2006.01255.x.

Hinkel, K.M., and Nelson, F.E., 2003, Spatial and temporal patterns of active layer thickness at Circumpolar Active Layer Monitoring (CALM) sites in northern Alaska, 1995–2000: Journal of Geophysical Research; Atmospheres, v. 108, no. D2, p. ALT 9–1 to ALT 9–13, http://dx.doi.org/10.1029/2001jd000927.

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

Homer, Collin, Huang, Chengquan, Yang, Limin, Wylie, Bruce, and Coan, Michael, 2004, Development of a 2001 National Land-Cover Database for the United States: Photogrammetric Engineering and Remote Sensing, v. 70, no. 7, p. 829–840, http://dx.doi.org/10.14358/PERS.70.7.829.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E.A.G., Ping, C.-L., Schirrmeister, L., Grosse, G., Michaelson, G.J., Koven, C.D., O'Donnell, J.A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J., and Kuhry, P., 2014, Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps: Biogeosciences, v. 11, no. 23, p. 6573–6593, http://dx.doi.org/10.5194/bg-11-6573-2014.

Hugelius, G., Tarnocai, C., Broll, G., Canadell, J.G., Kuhry, P., and Swanson, D.K., 2013, The Northern Circumpolar Soil Carbon Database; Spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions: Earth System Science Data, v. 5, no. 1, p. 3–13, http://dx.doi.org/10.5194/essd-5-3-2013.

Hugelius, Gustaf, Routh, Joyanto, Kuhry, Peter, and Crill, Patrick, 2012, Mapping the degree of decomposition and thaw remobilization potential of soil organic matter in discontinuous permafrost terrain: Journal of Geophysical Research; Biogeosciences, v. 117, no. G2, article G02030, 14 p., http://dx.doi.org/10.1029/2011JG001873.

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

Johnson, K.D., Harden, J.W., McGuire, A.D., Clark, Mark, Yuan, Fengming, and Finley, A.O., 2013, Permafrost and organic layer interactions over a climate gradient in a discontinuous permafrost zone: Environmental Research Letters, v. 8, no. 3, letter 035028, 12 p., http://dx.doi.org/10.1088/1748-9326/8/3/035028.

Johnston, C.E., Ewing, S.A., Harden, J.W., Varner, R.K., Wickland, K.P., Koch, J.C., Fuller, C.C., Manies, Kristen, and Jorgenson, M.T., 2014, Effect of permafrost thaw on CO_2 and CH_4 exchange in a western Alaska peatland chronosequence: Environmental Research Letters, v. 9, no. 8, letter 085004, 12 p., http://dx.doi.org/10.1088/1748-9326/9/8/085004.

Jorgenson, M.T., Racine, C.H., Walters, J.C., and Osterkamp, T.E., 2001, Permafrost degradation and ecological changes associated with a warming climate in central Alaska: Climatic Change, v. 48, no. 4, p. 551–579, http://dx.doi.org/10.1023/A:1005667424292.

Jorgenson, M.T., Shur, Y.L., and Osterkamp, T.E., 2008, Thermokarst in Alaska, *in* Kane, D.L., and Hinkel, K.M., eds., Proceedings of the Ninth International Conference on Permafrost, Fairbanks, Alaska, June 29 to July 3, 2008: Institute of Northern Engineering, University of Alaska-Fairbanks, p. 869–876.

Jorgenson, M.T., Shur, Y.L., and Pullman, E.R., 2006, Abrupt increase in permafrost degradation in Arctic Alaska: Geophysical Research Letters, v. 33, no. 2, letter L02503, 4 p., http://dx.doi.org/10.1029/2005gl024960.

Kasischke, E.S., and Johnstone, J.F., 2005, Variation in postfire organic layer thickness in a black spruce forest complex in interior Alaska and its effect on soil temperature and moisture: Canadian Journal of Forest Research, v. 35, no. 9, p. 2164–2177, http://dx.doi.org/10.1139/X05-159.

Kasischke, E.S., Verbyla, D.L., Rupp, T.S., McGuire, A.D., Murphy, K.A., Jandt, Randi, Barnes, J.L., Hoy, E.E., Duffy, P.A., Calef, Monika, and Turetsky, M.R., 2010, Alaska's changing fire regime—Implications for the vulnerability of its boreal forests: Canadian Journal of Forest Research, v. 40, no. 7, p. 1313–1324, http://dx.doi.org/10.1139/X10-098.

LANDFIRE, 2008, Existing vegetation type layer (ver. 1.1.0): LANDFIRE spatial data, accessed December 15, 2014, at http://landfire.cr.usgs.gov/viewer/.

Mann, D.H., Rupp, T.S., Olson, M.A., and Duffy, P.A., 2012, Is Alaska's boreal forest now crossing a major ecological threshold?: Arctic, Antarctic, and Alpine Research, v. 44, no. 3, p. 319–331, http://dx.doi.org/10.1657/1938-4246-44.3.319.

Marchenko, Sergei, Romanovsky, Vladimir, and Tipenko, Gennady, 2008, Numerical modeling of spatial permafrost dynamics in Alaska, *in* Kane, D.L., and Hinkel, K.M., eds., International Conference on Permafrost, 9th, Fairbanks, Alaska, June 29–July 3, 2008, Proceedings: Fairbanks, Alaska, Institute of Northern Engineering, University of Alaska, Fairbanks, p. 190–204.

Martin, M.P., Wattenbach, M., Smith, P., Meersmans, J., Jolivet, C., Boulonne, L., and Arrouays, D., 2011, Spatial distribution of soil organic carbon stocks in France: Biogeosciences, v. 8, no. 5, p. 1053–1065, http://dx.doi.org/10.5194/bg-8-1053-2011.

McConnell, N.A., Turetsky, M.R., McGuire, A.D., Kane, E.S., Waldrop, M.P., and Harden, J.W., 2013, Controls on ecosystem and root respiration across a permafrost and wetland gradient in interior Alaska: Environmental Research Letters, v. 8, no. 4, letter 045029, 11 p., http://dx.doi.org/10.1088/1748-9326/8/4/045029.

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

Mu, Cuicui, Zhang, Tingjun, Schuster, P.F., Schaefer, Kevin, Wickland, K.P., Repert, D.A., Liu, Lin, Schaefer, Tim, and Cheng, Guodong, 2014, Carbon and geochemical properties of cryosols on the North Slope of Alaska: Cold Regions Science and Technology, v. 100, p. 59–67, http://dx.doi.org/10.1016/j.coldregions.2014.01.001.

Natali, S.M., Schuur, E.A.G., and Rubin, R.L., 2012, Increased plant productivity in Alaskan tundra as a result of experimental warming of soil and permafrost: Journal of Ecology, v. 100, no. 2, p. 488–498, http://dx.doi.org/10.1111/j.1365-2745.2011.01925.x.

Natali, S.M., Schuur, E.A.G., Trucco, Christian, Hicks Pries, C.E., Crummer, K.G., and Baron Lopez, A.F., 2011, Effects of experimental warming of air, soil and permafrost on carbon balance in Alaskan tundra: Global Change Biology, v. 17, no. 3, p. 1394–1407, http://dx.doi.org/10.1111/j.1365-2486.2010.02303.x.

National Research Council, 2014, Opportunities to use remote sensing in understanding permafrost and related ecological characteristics; Report of a workshop: Washington, D.C., The National Academies Press, 52 p.

O'Donnell, J.A., Romanovsky, V.E., Harden, J.W., and McGuire, A.D., 2009, The effect of moisture content on the thermal conductivity of moss and organic soil horizons from black spruce ecosystems in interior Alaska: Soil Science, v. 174, no. 12, p. 646–651, http://dx.doi.org/10.1097/SS.0b013e3181c4a7f8.

Osterkamp, T.E., Jorgenson, M.T., Schuur, E.A.G., Shur, Y.L., Kanevskiy, M.Z., Vogel, J.G., and Tumskoy, V.E., 2009, Physical and ecological changes associated with warming permafrost and thermokarst in interior Alaska: Permafrost and Periglacial Processes, v. 20, no. 3, p. 235–256, http://dx.doi.org/10.1002/ppp.656.

Pastick, N.J., Jorgenson, M.T., Wylie, B.K., Minsley, B.J., Ji, Lei, Walvoord, M.A., Smith, B.D., Abraham, J.D., and Rose, J.R., 2013, Extending airborne electromagnetic surveys for regional active layer and permafrost mapping with remote sensing and ancillary data, Yukon Flats ecoregion, central Alaska: Permafrost and Periglacial Processes, v. 24, no. 3, p. 184–199, http://dx.doi.org/10.1002/ppp.1775.

Pastick, N.J., Jorgenson, M.T., Wylie, B.K., Nield, S.J., Johnson, K.D., and Finley, A.O., 2015, Distribution of near-surface permafrost in Alaska; Estimates of present and future conditions: Remote Sensing of Environment, v. 168, p. 301–315, http://dx.doi.org/10.1016/j.rse.2015.07.019.

Pastick, N.J., Jorgenson, M.T., Wylie, B.K., Rose, J.R., Rigge, Matthew, and Walvoord, M.A., 2014, Spatial variability and landscape controls of near-surface permafrost within the Alaskan Yukon River Basin: Journal of Geophysical Research; Biogeosciences, v. 119, no. 6, p. 1244–1265, http://dx.doi.org/10.1002/2013JG002594.

Pastick, N.J., Rigge, Matthew, Wylie, B.K., Jorgenson, M.T., Rose, J.R., Johnson, K.D., and Ji, Lei, 2014, Distribution and landscape controls of organic layer thickness and carbon within the Alaskan Yukon River Basin: Geoderma, v. 230–231, p. 79–94, http://dx.doi.org/10.1016/j.geoderma.2014.04.008.

Ping, C.-L., Michaelson, G.J., Jorgenson, M.T., Kimble, J.M., Epstein, Howard, Romanovsky, V.E., and Walker, D.A., 2008, High stocks of soil organic carbon in the North American Arctic region: Nature Geoscience, v. 1, no. 9, p. 615–619, http://dx.doi.org/10.1038/ngeo284.

Riahi, Keywan, Rao, Shilpa, Krey, Volker, Cho, Cheolhung, Chirkov, Vadim, Fischer, Guenther, Kindermann, Georg, Nakicenovic, Nebojsa, and Rafaj, Peter, 2011, RCP 8.5—A scenario of comparatively high greenhouse gas emissions: Climatic Change, v. 109, nos. 1–2, p. 33–57, http://dx.doi.org/10.1007/s10584-011-0149-y.

Schaefer, Kevin, Lantuit, Hugues, Romanovsky, V.E., Schuur, E.A.G., and Witt, Ronald, 2014, The impact of the permafrost carbon feedback on global climate: Environmental Research Letters, v. 9, no. 8, letter 085003, 9 p., http://dx.doi.org/10.1088/1748-9326/9/8/085003.

Schaefer, Kevin, Zhang, Tingjun, Bruhwiler, Lori, and Barrett, A.P., 2011, Amount and timing of permafrost carbon release in response to climate warming: Tellus; Series B, Chemical and Physical Meteorology, v. 63B, no. 2, p. 165–180, http://dx.doi.org/10.1111/j.1600-0889.2011.00527.x.

Schuur, E.A.G., Bockheim, James, Canadell, J.G., Euskirchen, Eugenie, Field, C.B., Goryachkin, S.V., Hagemann, Stefan, Kuhry, Peter, Lafleur, P.M., Lee, Hanna, Mazhitova, Galina, Nelson, F.E., Rinke, Annette, Romanovsky, V.E., Shiklomanov, Nikolay, Tarnocai, Charles, Venevsky, Sergey, Vogel, J.G., and Zimov, S.A., 2008, Vulnerability of permafrost carbon to climate change—Implications for the global carbon cycle: BioScience, v. 58, no. 8, p. 701–714, http://dx.doi.org/10.1641/B580807.

Schuur, E.A.G., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J., Hugelius, G., Koven, C.D., Kuhry, P., Lawrence, D.M., Natali, S.M., Olefeldt, D., Romanovsky, V.E., Schaefer, K., Turetsky, M.R., Treat, C.C., and Vonk, J.E., 2015, Climate change and the permafrost carbon feedback: Nature, v. 520, no. 7546, p. 171–179, http://dx.doi.org/10.1038/nature14338.

Shur, Y.L., and Jorgenson, M.T., 2007, Patterns of permafrost formation and degradation in relation to climate and ecosystems: Permafrost and Periglacial Processes, v. 18, no. 1, p. 7–19, http://dx.doi.org/10.1002/ppp.582.

Smit, B., Burton, I., Klein, R.J.T., and Street, R., 1999, The science of adaptation; A framework for assessment: Mitigation and Adaptation Strategies for Global Change, v. 4, nos. 3–4, p. 199–213, http://dx.doi.org/10.1023/A:1009652531101.

Soil Survey Staff, 1999, Soil taxonomy; A basic system of soil classification for making and interpreting soil surveys (2d ed.): U.S. Department of Agriculture, Natural Resources Conservation Service, Agriculture Handbook, no. 436, 871 p., http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051232.pdf.

Soil Survey Staff, 2012, General soil map of Alaska—STATSGO data: U.S. Department of Agriculture, Natural Resources Conservation Service, accessed [date], at http://websoilsurvey.nrcs.usda.gov/.

Stocker, T.F., Qin, Dahe, Plattner, G.-K., Tignor, M.M.B., Allen, S.K., Boschung, Judith, Nauels, Alexander, Xia, Yu, Bex, Vincent, and Midgley, P.M., eds., 2013, 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, United Kingdom, Cambridge University Press, 1535 p. [Also available at http://www.ipcc.ch/report/ar5/wg1/.]

Treat, C.C., Wollheim, W.M., Varner, R.K., Grandy, A.S., Talbot, J., and Frolking, S., 2014, Temperature and peat type control CO_2 and CH_4 production in Alaskan permafrost peats: Global Change Biology, v. 20, no. 8, p. 2674–2686, http://dx.doi.org/10.1111/gcb.12572.

Turetsky, M.R., Kane, E.S., Harden, J.W., Ottmar, R.D., Manies, K.L., Hoy, Elizabeth, and Kasischke, E.S., 2011, Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands: Nature Geoscience, v. 4, no. 1, p. 27–31, http://dx.doi.org/10.1038/ngeo1027.

University of Alaska-Fairbanks, Geophysical Institute Permafrost Lab [GIPL], 2011, Simulated active layer thickness: Fairbanks, Alaska, Arctic Landscape Conservation Cooperative, http://arcticlcc.org/products/spatial-data/show/simulated-active-layer-thickness.

Walvoord, M.A., Voss, C.I., and Wellman, T.P., 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, v. 48, no. 7, article W07524, 17 p., http://dx.doi.org/10.1029/2011WR011595.

Wellman, T.P., Voss, C.I., and Walvoord, M.A., 2013, Impacts of climate, lake size, and supra- and sub-permafrost groundwater flow on lake-talik evolution, Yukon Flats, Alaska (USA): Hydrogeology Journal, v. 21, no. 1, p. 281–298, http://dx.doi.org/10.1007/s10040-012-0941-4.

Wickland, K.P., and Neff, J.C., 2008, Decomposition of soil organic matter from boreal black spruce forest; Environmental and chemical controls: Biogeochemistry, v. 87, no. 1, p. 29–47, http://dx.doi.org/10.1007/s10533-007-9166-3.

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

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

Yoshikawa, Kenji, and Hinzman, L.D., 2003, Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska: Permafrost and Periglacial Processes, v. 14, no. 2, p. 151–160, http://dx.doi.org/10.1002/ppp.451.

Zhuang, Q., McGuire, A.D., Melillo, J.M., Clein, J.S., Dargaville, R.J., Kicklighter, D.W., Myneni, R.B., Dong, J., Romanovsky, V.E., Harden, J., and Hobbie, J.E., 2003, Carbon cycling in extratropical terrestrial ecosystems of the Northern Hemisphere during the 20th century—A modeling analysis of the influences of soil thermal dynamics: Tellus; Series B, Chemical and Physical Meteorology, v. 55B, no. 3, p. 751–776, http://dx.doi.org/10.1034/j.1600-0889.2003.00060.x.