Spring 5-19-2017

The Relationship between Wildfire Dynamics and Soil Carbon in Boreal Forests of Alaska: Forest Management for Emissions Reduction in a Changing Climate

James D. Heaster
University of San Francisco, jim.heaster@gmail.com

This Master's Project

The Relationship between Wildfire Dynamics and Soil Carbon in Boreal Forests of Alaska: Forest Management for Emissions Reduction in a Changing Climate

By:

James Douglas Heaster

Is submitted in partial fulfillment of the requirements
for the degree of:

Master of Science
in
Environmental Management

at the

University of San Francisco

Submitted:

14 May 2017

James D. Heaster Date

Received:

John Callaway, PhD Date

Acknowledgments

This Master's Project represents the culmination of my graduate studies at the University of San Francisco. I would like to express my gratitude to my graduate advisor Dr. John Callaway for his guidance, patience, motivation, and input in helping me to understand this complex issue.

I would also like to sincerely thank Dr. David Saah, Director of the USF Geospatial Science Department for his good humor, guidance, inspiration, and for the contribution of his vast knowledge of geospatial science to my GIS analyses during this project. Without his inputs and expertise, much of this paper would not have been possible.

Table of Contents

Acknowledgments 2
Abstract: 5
Section 1.0- Introduction/ Site Background 6
Regional Topography 7
Soil Organic Carbon 7
Permafrost Dynamics and Thermokarst Processes 9
Forest Composition & Succession Dynamics 11
Human Influences/ Land Use 14
Relevance to Environmental Management 17
Section 2.0 METHODS 19
2.1 Datasets 19
2.1.1 Permafrost Data 20
2.1.2 Northern Circumpolar Soil Carbon and Thermokarst Data 21
2.1.3 Alaska Wildfire Data 22
2.2 GIS Tools & Methods 22
2.2.1 Clip Geoprocessing Tool 23
2.2.2 Intersect Geoprocessing Tool 24
2.2.3 Dissolve Geoprocessing Tool 25
Section 3.0- Evidence 26
3.1 Soil Carbon Dynamics 26
Soil Taxa and Carbon Storage Characteristics 27
Climate Influences to Soil 30
Topographical Influences on Soil Carbon Dynamics 33
3.2 Permafrost Dynamics 35
Permafrost Recovery Capacity 38
Thermokarst Effects on Topography and Carbon Cycling 39
Loss of Organic Soil Layers Effect on Permafrost and Ecological Recovery Processes 42
Fire Interactions with Permafrost 44
3.3 Climate Change Influences on Carbon and Fire Cycles 46
Influences of Temperatures and the Pacific Decadal Oscillation (PDO) on Carbon/ Fire Cycles 46
Climate Change Impacts on Vegetation 49

Climate Change Impacts on Fire Cycles & Soil Carbon Dynamics 51
3.4 Role of Wildfire and Forest Succession 54
Post-Fire Successional Dynamics 58
Fire Effects on Soil Carbon 60
Soil Carbon Effects on Succession 64
3.5 Human Influences 65
Human Ignitions from Land Use 66
Section 4.0- Discussion 68
Soil Carbon Dynamics 69
Permafrost Dynamics 70
Successional Trajectory and Subsistence Species 71
Data Gaps, Spatial Modeling Limitations, and Influencing Factors 74
Significant Counter-Findings 77
Regional Significance 78
Section 5.0- Recommendations 79
1. Fire Suppression Policies/ Actions 80
2. Forestry Management/ Land Use Changes 81
3. Ongoing Monitoring & Data Needs 83
Section 6.0- Conclusions 84
References Cited 87
GIS Data Resources/ References Cited 94
Supporting Figures & Tables (from Literature) 95

Abstract:

The boreal region of Alaska has vast forests spanning hundreds of thousands of square kilometers in the central portion of the state that is prone to large stand replacing summer wildfires. The region stores considerable quantities of terrestrial carbon sequestered in soil horizons down to 1 meter in depth that are strongly influenced by a combination of climate change, permafrost dynamics, vegetative composition, and fire regimes. Data and literature establish that the boreal region of Alaska (and the rest of the Arctic) has been steadily warming at a rate nearly double that of lower latitudes. This warming has resulted in larger fires defined by shorter return intervals. This altered fire regime places the vast stocks of organic soil carbon at risk to greater degrees of combustion, potentially contributing millions more tons of CO_2 to the atmosphere in the Arctic region.

Between 2000-2015 roughly 5% (~28,000 km^2) of the over 560,000 km^2 of the boreal region burned, raising CO_2 levels and supporting a positive feedback loop between climate and fires; when considering that this region of Alaska is larger than the state of California (~420,000 km^2) these emissions are significant. Mean summer temperatures have risen by 1.4° C over the last 100 years, resulting in shorter fire return intervals characterized by more severe and intense, longer fire seasons. This warming is driving more pronounced permafrost degradation that is altering both the extent and depth of regional permafrost layers, increasing labile carbon stocks that serve as additional fuel pools for fires. While permafrost layers are fluctuating more frequently, the warmer temperatures are supporting increased vegetation growth with expansion of the boreal forest into landscapes that were previously hostile, increasing novelty in these area's fire regimes and subsequent emissions. As fire activity increases in the region, forest composition is being altered toward a greater dominance by deciduous rather than coniferous trees, a development that is increasing soil carbon levels as these stands mature. Human suppression policies, despite being well intentioned, are driving more frequent and severe fires due to an unnatural buildup of fuels, especially around regional population centers. Because of these findings, I recommend closing critical data gaps with further data additions, changing timber harvesting and forest management policies, and reexamining fire suppression policies.

Section 1.0- Introduction/ Site Background:

Boreal forests comprise the largest ecoregion of Alaska and encompass over 560,000 km^2 in the central, north central, and southwestern portions of the state (Figure 1-1). The widely variable climate of Alaska (the coldest temperature on record was -62.2° C, the hottest temperature on record was 37.8° C), coupled with long and formidable winters creates an environment that fosters a unique and highly variable fire season in the boreal forest region of the state (http://www.weather.gov/arh/, http://afs.ak.blm.gov/).

The boreal forest region of Alaska has a record of small to large scale wildfires (Figure 6, Appendix A) that have been broadly dispersed throughout the region. During the first decade of the 21st century an average of 767,000 hectares per year burned, representing approximately 50% more terrestrial area consumed by fire than in decades since the 1940's (Kasischke et. al. 2010). Per Wendler and Martha (2009), the Fairbanks area (the largest city within the boreal region) has experienced an average 1.4° C increase in average summer temperatures throughout the region since the early part of the 20th century. Given that average temperatures in the interior portion of the state seem to be steadily increasing it is reasonable to conclude that there is a direct link between climate change and wildfire activity and carbon emissions within this region.

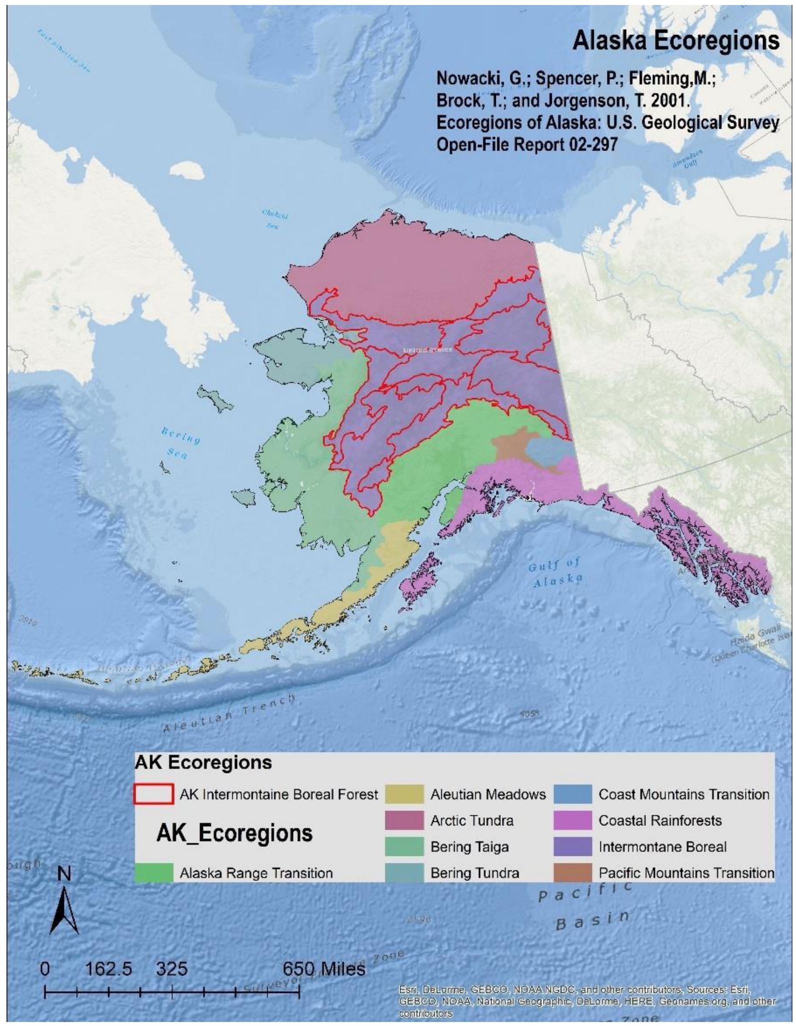


Figure 1-1: Map of the eco-regions of the state of Alaska. From: Nowacki et. al. 2001 and the U.S. Geological Survey Open-File Report 02-297.

Climate/ Soil Conditions

Alaska is home to three primary climates—Holarctic in the south central and southwestern portions of the state, Maritime in the Southeastern panhandle and Arctic on the northern edge of the boreal forest region (Johnson & Myanishi 2012; Alaska Interagency Fire Management Plan 2016). The boreal forest region is primarily Holarctic with the northern portion lying inside the Arctic Circle. Regionally this area has experienced a warming climate for the last century that has extended the growing season- expanding forest boundaries (Tape et. al. 2016) and altering phenological cycles of many endemic plant species (Root et. al. 2003). Additionally, ocean influenced atmospheric conditions like the Pacific Decadal Oscillation (PDO [Hartman & Wendler 2005]) have exerted noticeable influences on temperature and precipitation patterns of the region. While the region is defined by extremely cold winters with prolonged inversion periods that drive average temperatures well into double digit negative ranges, the winters are becoming shorter with the transition to spring and breakup seasons happening more rapidly. As summers get warmer and longer in the region, the literature postulates that the boreal forests that dominate the central portion of the region could migrate northward over taking tundra areas and altering the fire and carbon dynamics of these sub-regions.

Regional Topography

The boreal forest region in the central portion of Alaska (Figure 1-1) is bordered in the north by the Brooks Range, and on its southern and southwestern most portion by the Alaska and Talkeetna Ranges. Several major rivers flow through the region including the Yukon (in the north) and the Tanana and Nenana Rivers (central). These waterways serve as major transportation corridors for downed trees and other organic matter (Ding et. al. 2014) trapped in silt that are distributed by spring river swells that accompany the thawing period known as break up season. These rivers also form low lying areas that are generally more susceptible to fire influences than higher elevations such as foothills and alpine regions near the mountains (Turetsky et. al. 2014).

Soil Organic Carbon

The boreal region of Alaska contains carbon rich soils that range in concentration from one patch to another, and overall the region is defined by soils that store large amounts of carbon stocks (Hugelius et. al. 2013) that are the result of both the accumulation of detritus over time, slow decomposition rates, and permafrost stabilized deeper layers (B. Young et. al. 2016). Low-lying areas, are deposition zones of large amounts of organic carbon (USDA 1999) that tend to pool in certain soil taxa. These soil carbon layers are of concern as climate warming pushes permafrost layers deeper down into the soil horizon (Jorgenson et. al. 2015) with the result that greater quantities of labile carbon may become feed stock for future aggressive fire regimes. Fire's secondary influence on permafrost retreat and increased active layer depth will only become more pronounced in coming decades as warming temperatures favor increased fires, albedo changes, and greater radiative forcing that results in larger stocks of carbon from permafrost retreat (Randerson et. al. 2006; Shenoy et. al. 2011).

Currently substantial and rapid shifts in fire activity are occurring across the globe (Moritz et. al. 2012) and in boreal Alaska (McGuire et. al. 2009). The importance of fire cycles in driving carbon cycling and other ecosystem services is well documented within the body of researched literature; fire cycle vulnerabilities to climate change and fire's importance in terrestrial carbon cycling are well understood (A. Young et al. 2016). Wildfire is a major dynamic controlling long term soil carbon dynamics (Taş, 2014), and fires of sufficient severity discharge large quantities of soil bound carbon into the atmosphere (Brown et. al. 2016). Warming temperatures favor trends toward more very large wildfires (Stavros et al. 2014) that can cause habitat degradation over time. Severe ground level fires favor a receding of permafrost levels that liberate greater stocks of labile soil carbon available for combustion in proportion to the severity and size of wildfires (Moritz et. al. 2012). Although carbon stock densities are highly dependent on landscape type (Chien Liu et. al. 2008) the potential for these stocks to be at risk due to wildfire induced depletion has increased substantially in response to climate change (Brown, 2016). As more severe fires occur and more soil carbon stocks are released to the atmosphere, the potential exists to create a positive feedback loop (Stavros, 2014) in warming arising from the greenhouse effect that increased atmospheric CO_2 concentrations in the polar region may cause (Lorianty et. al. 2014). These greenhouse gasses could continue to alter future climate (Allen et. al 2010), and seasonal changes such as longer summers (Wendler & Shulski 2008) will contribute to a greater amount of carbon emissions in the coming decades.

Permafrost Dynamics and Thermokarst Processes

The boreal region is underlain by various extents of permafrost layers that interact with surface and shallow horizon soil carbon stocks. Per the permafrost map generated by Jorgensen and colleagues (2008), the permafrost extents present in the boreal region are continuous (>90% of underlain area), discontinuous (50-90%), sporadic (10-50%), isolated (0-10%) and absent. Permafrost distributions in this area is defined by patches and landscapes, since the entire region is not contiguously underlain by permafrost (Jorgenson et. al. 2008). Loss of permafrost because of climate and fire influences may result in landscape conversions to collapse scar bogs and muskeg due to thermokarst (Olefeldt et. al. 2015; Lara et. al. 2016). These permafrost layers that underlie the Central Tanana region and can be deleteriously affected by increased temperatures due to climate warming and are susceptible to effects from large, severe fires (Brown et. al. 2016). Permafrost layers are large stores of potentially labile soil carbon (Taş et. al. 2014) but are insulated by the overlaying organic soil layers. Fires of sufficient intensity can eliminate these layers (Taş, 2014) and although low intensity fires may result in ecosystem recovery to full pre-fire condition (Lorianty et. al. 2014), large severe wildfires can favor an absence of permafrost (Brown et. al. 2016).

Permafrost behavior can determine soil carbon content because retreating permafrost exposes new layers of soil carbon that are susceptible to more rapid drying during warmer summers (Ping et. al 2008). Continued warming may dry out these layers (Brown et. al. 2016) making them more vulnerable to combustion that will cause these layers to decrease in size and insulating capability (Harden et. al. 2000). The importance of the insulating soil organic carbon layer cannot be overstated since this layer can take thousands to tens-of-thousands of years to regenerate (Mack et. al. 2011), and store vast quantities of carbon that can contribute to the atmospheric greenhouse gas cycle, and alter the carbon cycle of the entire Arctic/ Holarctic biome (Lorianty et. al. 2014). The warming climate extends the summer and in some areas, decreases the amount of summer precipitation creating longer dry periods conducive to more frequent fires, and a loss of the insular organic layer overlaying permafrost (Taş et. al 2014, Wendler & Shulski 2008).

Permafrost layers provide a stabilizing influence on soil carbon stocks by inhibiting microbial decomposition, and freezing in soil strata limiting nutrient pools that are essential for surface biomass growth (N_2 being the primary nutrient followed by bioavailable labile carbon

[Boby et. al. 2010]). Permafrost layer integrity relies on two key factors: organic soil carbon layers and climatic influences, although fires exert a secondary influence, usually at the patch scale. Soil organic carbon layers are formed by biomass deposition of detritus that forms an insulating layer over the active layer (the soil stratigraphy directly over the permafrost layer that seasonally freezes and thaws), and these layers are most directly affected by fire activity (O'Donnell et. al. 2011). It should be noted that permafrost retreat proportionate to fire severity is not very well understood or the models for projecting such volumes are lacking in the ability to completely account for future climate trends.

Climate induced reduction in permafrost levels results in topographical distortions in landscapes (Olefeldt 2015). This topographical transformation process is called thermokarst and is directly influenced by permafrost dynamics, causing surficial deformation caused by the sudden or widespread decrease in permafrost (and thus the loss of associated frost heaving [Jorgenson et. al. 2015]). Thermokarst affects not only the obvious surface topography, often transforming affected areas into a network of streams and vernal pools called muskeg or collapse scar bogs, but it affects vegetation, and thus soil carbon stocks (Schuur et. al. 2009). Areas where thermokarst has occurred can become concentration points for carbon, and under the right climatic conditions, can become a short-term carbon source rather than a carbon sink (Balshi et. al. 2009). The altered hydrology of these areas can support novel successional trajectories that favor novel biomass composition profiles and thus affect either the rate and quantity of detritus deposition that forms the insulating layer of soil carbon that protects permafrost (Smith et. al. 2015). Permafrost areas directly correlate with thermokarst occurrence and vegetative and landform transformation. Thermokarst can significantly change ecosystem services by altering habitat and topography that species depend on (A. Young et. al. 2016), or change biomass composition within affected areas entirely (Brown et. al. 2015). However, over time the literature indicates that stabilization of the soil carbon cycle if effected by thermokarst alone, and under the right climatic conditions (conditions that favor stable permafrost cycles) these areas can recover on a patch scale to pre-thermokarst conditions (with native biomass composition and structure).

Landscape changes due to thermokarst are becoming more common in the boreal region (Jorgensen et. al. 2015; Olefeldt, 2016) as climate warms and increased mean summer temperatures become the norm (Wendler & Shulsky 2009). Thermokarst is somewhat related to carbon content as areas with higher soil carbon levels tend to be areas where thermokarst landscape changes occur more frequently (Tamocai et. al. 2009). When permafrost thaws and soil carbon levels increase (Schuur 2009) these regions can become fire prone over time because of the greater fuel load that increased soil carbon levels support (Mack et. al. 2004). Global circumpolar carbon levels that Olefeldt and fellow researchers (2016) and Hugelius and fellows (2013) compiled illustrate just how much soil carbon is stored in Arctic and Holarctic regions globally (Figure 5 in Appendix A). A relationship between soil carbon levels and regional susceptibility to thermokarst induced topographic deformation appears to exist, and areas with higher carbon levels are at a greater susceptibility to landscape transformation (Routh et. al. 2014; Liu et. al. 2014).

Forest Composition & Succession Dynamics

Because of the network of smaller rivers and streams and the soil characteristics, this area has broad dense forests of mixed dominance regionwide despite the harsh climate prevalent in the area (Natcher 2004). The northern edges of this region are predominantly tundra defined by grasses, shrubs, and forbes that flourish in the peat soil (Mack et. al. 2011). The boreal region is primarily dominated by black spruce (*Picea mariana*) stands that over lay some of the most carbon rich areas of the region (Johnstone et. al. 2010; B. Young et. al. 2016; Gaglioti et. al. 2016). These stands are vulnerable to influences from fire because of their flammability characteristics, shallow root systems, and clonal reproduction post-fire (Lloyd et. al. 2005). While these stands are well adapted to fire regimes with long return intervals defined by lower intensity (combustive energy) fire, they are ill adapted to fire regimes defined by high intensity and short return interval (Kelly et. al. 2013). The region is also home to smaller stands or mixed codominant stands of deciduous-conifer or deciduous species (Norris et. al. 2011). Many of these stands are found in areas where burn intervals have changed markedly over the last 1,000 years and constitute valuable habitat for vital big game species that residents depend on for subsistence (Nelson et. al. 2008). Tundra comprises the majority composition of northern areas of the boreal region (Hu et. al. 2006; Loranty et. al. 2014). Although spruce stands occur in patches in tundra areas, these areas are composed of mostly peatlands dominated by grasses and forbs and store significant quantities of carbon (Bret-Harte et. al. 2013). These areas are important to consider because as climate warms there is a potential for the northern expansion of forest lands into these areas (Tape et. al. 2016) and a novel fire regime could cause a pronounced increase in carbon emissions from these portions of the landscape that convert patches into carbon sources (Mack et. al. 2011).

Fire behavior itself is unique in Alaska in that crown (canopy fires that burn above the ground level) and ground fires can behave very differently than in other locations, particularly the lower 48 United States (Allen et al. 2010). Large "holdover" fires can continue to burn over the winter, insulated in the soil organic layer despite being covered by snow (Alaska Forest Service). This can cause permafrost to retreat to lower soil horizons such that during the spring thaw, a greater horizon layer of organic combustible material is exposed to drying in the spring and more vulnerable to fire over the warmer summer months (http://www.amidst.alaska.edu/pdf/forest_fires.pdf). These smoldering holdover fires can also be source points for new ignitions when weather conditions become favorable during the late spring- early summer months.

Stand replacing wildfires are a keystone disturbance in boreal forests of Alaska (Gaglioti et. al. 2016), and drive important biogeochemical and ecological cycles such as soil carbon cycling and ecological succession; however, these disturbances are becoming more frequent and erratic as climate changes (Moritz et. al. 2012; A. Young et. al. 2016). Wildfire is closely tied to climate (and to some lesser extent, vegetative) parameters, and shifting climatic conditions are contributing to novel fire cycles, particularly in the central boreal forest regions of the state (Gaglioti. 2016). Warming trends within the state are expected to drive more frequent and severe fires (Kasischke et. al 2010) despite the regional variability associated with fires (Stavros et. al. 2014). In 2004 and again in 2009, the state experienced exceptionally large fires when compared to previous years (Barrett et. al. 2011; Johnstone et. al. 2009). There is considerable research to show that soil carbon cycling is closely related to the severity of wildfire, whether it be in forest or adjacent tundra regions (Mack et. al. 2011), however a proportional relationship is poorly understood since there is no uniform measure of fire severity (Boby et. al 2010) that can be correlated to soil carbon loss due to fire.

While forest composition is influenced to an extent by climate change, composition is most effected by fire dynamics (Johnstone et. al. 2010). The dominant tree species of the boreal region are adapted to the general climatic conditions of the region, and do not show dramatic shifts in composition due to minor climatic fluctuations (Allen et. al. 2010). They are also adapted to a specific fire regime defined by return interval, severity, and intensity, and are more sensitive to changes in this cycle than to those from climate (Jain et. al. 2012) Fires that are more intense expose broader areas of mineral soils (Wang & Kemball 2010) that favor deciduous dominated forest stands in the near term, altering the flammability profile of the region for several hundred years as successional trajectories toward these types of forests progress (Chapin et. al. 2003). Where deciduous dominated stands become prevalent they reduce the flammability of these forest stands and exert positive influences on essential regional megafauna (Nelson et. al. 2008; Natcher et. al. 2007). Although fires may strip away insulating soil layers (thus affecting permafrost), deciduous favoring trajectories exert a stabilizing influence over the region's carbon stocks (Liu et. al. 2014) by quickly replenishing the feedstock for soil carbon (ground detritus). However, when these forest stands are codominant with black spruce stands, the more flammable black spruce can act as an accelerant (DeWilde & Chapin 2006) causing these stands to burn, with subsequent greater carbon emissions.

In addition to combusting large quantities of soil carbon which can alter carbon cycling throughout the arctic (Lorianty et. al. 2014), increased wild fires may favor successional trajectories that result in the partial replacement of conifer stands with deciduous and shrub dominated stands (Shenoy 2011). More severe fires tend to occur in stands that are of a homogenous composition or largely dominated by coniferous tree species (Calef et. al. 2015). Stands that have been homogenized by human activities tend to be at a greater risk of fires during longer drier summers than stands where there is a mix of native deciduous species (Calef, 2015). During severe fires, many stands show earlier recruitment of deciduous tree species and bushes during early successional stages (Boby et. al. 2010) which makes recovering stands less fire prone to future fire incidents, as the deciduous dominated stands are more fire resistant (North & Hurteau 2011), and when fires do occur there is a higher mortality among young conifers that are more susceptible to ground level fire activity (Dash et. al. 2016). In the short term, slightly modified successional trajectories favoring deciduous over conifer species may be beneficial to stabilizing soil carbon stocks, as these stands are less prone to frequent fires which can give the landscape time to stabilize carbon levels post-fire (Kelly et. al. 2013). This succession can also be beneficial to providing a vegetative control to fire occurrence (Kelly, 2013; Young, 2016). That is not to say that eventually fire prone areas will be entirely dominated by deciduous species, some areas have shown an adaptation to cycles of extreme fire seasons or regimens that may last decades or centuries with conifer stands remaining the dominant tree species (Kelly, 2013).

Fire Cycle Influences on Climate

The boreal region fire season was previously defined by long return interval, low intensity, and moderately severe fires (Kelly 3013). Fires in this region tend to be a mix of both canopy and ground fires, with the former being the cause of increased tree mortality (Bret-Harte et. al. 2013) and ground fires being the source of the greatest carbon emission from these disturbance events. Fires are becoming more frequent in this region (Moritz et. al. 2012) and thus emitting more CO_2 to the atmosphere in the polar region. Current data (Alaska Fire Service) indicates that fire occurrences have increased from previously severe fire events in the 1950's, and if this trend continues, then emissions can be expected to increase dramatically by 2100. More frequent and severe fires, and affect the overall health of the forest, because as temperatures rise, forest stands become increasingly vulnerable to background mortality (Allen et. al. 2010) which can lead to a greater quantity of understory fuel. As previously stated, warming can cause permafrost layers to retreat and surface soils desiccate, adding an additional source of combustible materials (Mack et. al. 2011). Connectivity between large patches may also be increased as higher levels of "dead and down" trees coupled with drier shrubs and grasses can create a large surficial under-burden of available fuels that can contribute to larger than expected fires (A. Young, 2016). This spatial alteration of the landscape fuel load can change fire regime dynamics proportionate to the level of alteration (Dash et. al. 2016) such that novel fire regimes may emerge and become a new reality with the stresses of continued climatic shift (Kasischke et. al. 2010).

Human Influences/ Land Use

The boreal region is home to several groups of Athabaskan native peoples and residents of European or Russian descent that all depend on local resources and game to survive (Nelson 2008). Increased quantities of CO_2 in the atmosphere (a result of greater fire activity that combusts larger stocks of soil organic carbon) that encourages formation of positive feedback loops between fire activity and climate warming will have noticeable effects on regional populations (Johnson & Myanishi 2012). These affects can be negative through the loss of forest land and associated ecosystem services to fire, economic losses from decreased recreational land use, or increased risks to life and property in remote areas where fire suppression crews have little or no access. Effects to regional populations can also be positive—fires in remote areas that burn with sufficient intensity can increase forage for big game animals (through deciduous favoring succession) harvested for subsistence, effective forest management can preserve majority percentages of recreational tracts, and firefighting can provide much needed income to smaller communities. Effective suppression polices can serve to protect habited areas while preserving the appropriate disturbance cycle in the ecosystem without letting it get out of control.

The largest number of human caused fires often occur within certain distances of habited towns, major roads, and recreational use areas (Calef et .al 2008). Human land uses can support increasing fire regimes, or they can inhibit the spread of large fires through management practices that support the removal of fuel pools. Human suppression activities that focus on total suppression or critical suppression (suppressing more than 95% of fires [Alaska Interagency Fire Management Plan 2016]) can result in fuels build up over time that support large, catastrophic wildfires that pose direct risks to communities, and particularly remote or isolated communities such as Galena and Fort Yukon. In contrast where these fuels can be removed through unrestrictive permitting, timber harvesters can bring out dead and down or remove older dying or sick trees for firewood use, thus the forest stand can be effectively thinned to prevent large fires (Natcher 2004). In agricultural areas (such as Delta Junction) limited use of burning to clear grain fields or encouraging planting of less flammable native deciduous species to diversify forest composition may help to decrease fire risks in these communities (although such measures would have only a limited local effect on fire reduction potential).

Wildfire effects the regional megafauna through degradation of ecosystem services (habitat) and changes in biomass composition (forage) that can initially decrease essential game populations (although these tend to recover in the long term) (Nelson et. al. 2008; Tape et. al. 2016). Affects to this megafauna directly impact human populations in the region that practice total and semi-subsistence lifestyles (Natcher 2004) and will undoubtedly contribute economic losses in the form of lost revenue from limited hunting licenses in the future if these game populations become less stable due to increased fire activity.

Geospatial Analyses & Data

The relationship between wildfire severity and geography has been geospatially analyzed in the literature, but few articles deal with a direct correlation between the spatial relationship between fire severity and soil carbon release from a technological modeling and hence predictive stand point. High latitude ecoregions are key carbon storage areas in the global carbon cycle (Mack, 2011), however, estimates of global carbon stocks have not adequately addressed estimates of soil organic carbon (SOC) in permafrost affected regions, or the unique pedogenic processes that affect these soils (Hugelius et. al. 2013). Spatial modeling is a valuable tool to assess the relationships between soil carbon and wildfire on both a local and global scale and despite inefficiencies in some models, provides an overall understanding of climate induced changes to fire and soil carbon cycles (Rogers et. al. 2014; Prentice et. al. 2011).

Modeling of forest stand compositions and fire's affect thereto accounts for fire spread from the ground to the canopy using empirical relations between burn intensity, scorch height, and percent crown burned and is able to show fire effects under a range of fire intensity conditions (Miquelajauregui et al. 2016). The result of this model shows that forest stand structure is one of the factors influencing boreal fire severity variations (Miquelajauregui; 2016). Dash and fellow researchers used geospatial modelling and anlysis to show that land cover spatial arraingement exerted greater influences on boreal fire regimes when climatic shifts favored increased burning (Dash et. al. 2016) and Kasischke and Turetsky (2006) showed that seasonal burning patterns differd across ecozones influenced by climate warming. This GIS (Geospatial Information Systems) analysis ultimately showed that large fires burn in coniferous stands and that fuel arrangement was a deciding factor in the length and breadth of individual fires (Dash, 2016). Satellite data is also quite useful in locating ignition points and thus contributing to the efficiency of suppression efforts—filling data gaps in understanding fire dynamics and dates of ignition in regions with scant fire data and correcting inconsistencies in fire databases (Benali et. al. 2016).

Modeling of carbon also identifies trends over time and is useful in predicting future emissions based on present soil carbon and fire data (Rogers, 2014). Although the Northern Circumpolar Soil Carbon Database (NCSCD [Hugelius et. al. 2013]) lacks annual carbon level depth measuements, it is still useful for informing predictions of future relationships and behaviors between fire and soil carbon. Goetz and fellow researchers (2007) showed with modeling that a positive feedback loop between soil carbon combustion by fire and future warming is a distinct possibility (Goetz et. al. 2007) but a negative feedback loop caused by increased albedo (radiative forcing of solar energy to the ground) is potentially likely as well (2007). Modeling has also shown that terrestrial carbon storage at present is 821PgC less than in the last glacial maximum, with vegetation expanding rapidly into areas where glacial retreat has occurred, thus increasing terrestrial carbon storage (Kaplan et. al. 2002). Interestingly, modeling has supported the conclusion that fire regimes did not differ noticeably with the arrival of European settlers to the region, in fact the introduction of European type agriculture (albeit on a limited scale given Alaska's climate) contributed to a decrease in burning coincident with agricultural monoculture (Prentice et. al. 2011).

GIS tools are valuable assets to determine how land cover mosaics can decrease fire spread when these mosaics act as natural fire breaks by their composition (again deciduous dominated stands tend to be less fire prone under normal conditions [Benali et. al. 2016]). Given this relationship to spatial arrangement, understanding where a fire is initially ignited and its projected path can save millions of dollars in loss of property, ecosystem services, and can mitigate risks to human life (Benali, 2016). To that end, satellite data is a very effective point (Prentice et. al. 2011) tool for initial tracking of fires, but unfortunately does not provide much information regarding a relationship between fuels, stand composition, and fire behavior (Benali, 2016). Satellite imagery is also useful in determining how human management activities may have caused fuel build ups that make certain regions more prone to fire activity in the future (Gaglioti et. al. 2016). Wildfire is defined by complex interactions between vegetation, terrain, climate, and human factors such as management and suppression strategies (Chapin et. al. 2003). Technology can provide the capabilities to analyze such complex interactions to drive or alter policy for the greatest benefit of the surrounding landscape. Monitoring of such factors as vegetation to determine if excessive fuel build up is occurring, or if human fire management activities are suppressing fires in some areas while encouraging it in others, are invaluable in establishing factors that may determine the level of soil carbon cycling (Dash, 2016). There are limitations though as gaps in atmospheric carbon monitoring require higher density monitoring of soil carbon stocks, as currently these stocks can only be inferred from atmospheric CO_2 and CH_4 concentrations, and then at the continental scale (Birdsey et. al. 2009).

Relevance to Environmental Management

Greater levels of carbon emissions from climatically and anthropogenically induced increases in wildfire activity will have a pronounced effect on ecosystem services and functioning in the coming century (Davidson & Janssens 2006). Changes in biomass composition and expansion of the current range of boreal forests will affect human and animal populations alike thus requiring altered management strategies to insure abundance for coming generations (Tape 2016). The potentially self-sustaining positive feedback loop created between climate and soil carbon emissions driven by increased fires (Liu et. al. 2014) will negatively affect land usability and thus negatively impact both current and future human populations. Regional flora diversity is essential to healthy habitat (Natcher et. al. 2007) and this biodiversity will be threatened in the near term by increased wildfire, thus necessitating understanding of the interrelational dynamics of climate on soil carbon loss due to wildfire.

Human fire suppression has altered regional (Calef et. al. 2015) fuel stocks by favoring a buildup of fuels in and around populated areas (2015). This is concerning because the areas defined as the most economically valuable or the most sensitive based on current human use, are also the most vulnerable areas of the region to fire (DeWilde & Chapin 2006). Finding the most practical, effective, and implementable forest management methods based on an understanding of this relationship is critical to forest preservation and the protection of economic interests and human life (Calf et. al. 2008). Using the best available geospatial data and tools to gain further understanding of this relationship is not only interesting for the increase of knowledge, but essential for the effective management towards abundance of the boreal region ecosystem and services.

The goal of this paper is to evaluate the interrelationship between more frequent seasonal fires and increased carbon emissions from soil stocks to answer my primary research question:

> "***How will key terrestrial processes susceptible to climate change influence soil carbon emissions resulting from novelty in fire distribution and frequency in the boreal region of Alaska?"***

To evaluate my general research question, I will answer the following five more concise supporting questions using literature reviews and GIS data:

1. What is the carbon storage capacity of regional soils and does fire or climate exert the greatest influence on carbon emissions and alter soil organic carbon storage capacities?
2. How do permafrost dynamics influence soil carbon stocks, landscape transformation through thermokarst, surface vegetation composition, and carbon emissions from fire activity on patch and regional scales?

3. How will an altered climate as defined by longer, warmer summers alter biomass composition, wildfire, and permafrost dynamics to increase or decrease carbon emissions on a patch and regional scale?
4. Can patch and landscape scale successionary shifts in forest stand structure and associated ecological forces act to increase or limit fire regime novelty, restore permafrost integrity (thus reversing thermokarst), and limit fire induced carbon emissions in the region?
5. How do human land use practices and suppression activities influence fire cycles on the patch and landscape scale and do specific, regional unique land use practices increase, decrease, or result in a net neutral output of carbon emissions from fire and/ or landscape alteration?

Evidence that answers these sub-questions will support recommendations for future land use and forestry management to produce abundance for human populations in the region, preserve instrumental and intrinsic regional forest value, and mitigate carbon emissions that spur climate change by supporting positive feedback loops created by fires and carbon emissions.

Section 2.0 METHODS

2.1 Datasets

Specifically addressing the five main sub questions was accomplished through an exhaustive literature review that was supported by geospatial analyses using ArcGIS® software. To address the first and second questions regarding the carbon storage capacity of regional soils (USDA soil taxonomy was primarily used to answer this sub question) and how permafrost dynamics influence soil carbon stocks, landscape transformation through thermokarst, surface vegetation composition, and carbon emissions from fire activity on patch and regional scales, I utilized data from the Northern Circumpolar Carbon Database compiled by Hugelius et. al. (2013), and data from Olefeldt et, al. (2016) regarding thermokarst areas in Alaska. Data from Jorgenson et. al. (2008) was the most critical dataset showing permafrost extents and spatial locations within the Alaskan boreal region. To answer the third and fourth questions of how warmer, longer summers will affect biomass composition and extent, permafrost levels, and regional carbon dynamics and fire driven emissions, I relied primarily upon data from literature reviews that directly addressed climate change. These data allowed me to elucidate relationships between increased mean temperatures and permafrost retreat or aggradation, and how this process affects and is affected by soil carbon layers. These data also informed the response of soil carbon layers to altered vegetation profiles, i.e., changes in both composition and expansion of forest landscapes. Literature data were compared to GIS data on fires containing spatial and temporal attributes to illustrate the time and location of fire occurrence to show relationships to fire induced carbon emissions. These data were particularly useful in answering my fourth question of how patch and landscape scale successionary shifts in forest stand structure and associated ecological forces act to increase or limit fire regime novelty, restore permafrost integrity (thus reversing thermokarst), and influence fire induced carbon emissions in the region. I also used data from the Alaska fire service to show the relationship between increased temperatures and fire occurrence and size.

To answer my final question of how human land use practices and suppression activities influence fire cycles on the patch and landscape scale and whether specific, regionally unique land use practices increase, decrease, or result in a net neutral output of carbon emissions from fire and/ or landscape alteration, I relied on literature and infrastructure data. Data from the Alaska Department of Transportation and the United States Census bureau provided spatial information about road and town locations and when geoprocessed, showed buffer zones around these areas that provide visual aids in understanding my primary recommendations for decreases in suppression activities farther than 10 km away from roads and towns, and changes in forest management policies regarding timber harvesting and forest floor clearing.

2.1.1 Permafrost Data

Data regarding permafrost extents throughout the boreal region of Alaska (current to 2008) was obtained from the Permafrost Characteristics Map of Alaska (Jorgenson et. al. 2008). These data were used to spatially define permafrost locations and extents throughout the area of analysis in central Alaska to support answering the question of how permafrost dynamics influence carbon cycles. Attributes of permafrost classifications as continuous (>90% permafrost cover by area), discontinuous (50-90%), sporadic (10-50%), isolated (>0-10%), and absent (non-detectable) and are delineated as GIS polygons (shapefiles) and contain areas and perimeters of permafrost. As a stand-alone dataset, this provides a qualitative representation of the location and regional extent of boreal permafrost. The primary weakness of this shapefile is a lack of a temporal aspect (the data do not contain a time aspect that would allow for quantification of extent changes over time).

2.1.2 Northern Circumpolar Soil Carbon and Thermokarst Data

Soil carbon concentrations throughout the entire circumpolar region of the globe are contained as data in the Northern Circumpolar Soil Carbon Database (NCSCD) (Hugelius et. al. 2014). GIS analysis of these data showed the dynamic relationship between soil carbon and wildfire, and support conclusions about carbon emissions due to fire activity. This shapefile contains data regarding soil carbon concentration (SOCC) and soil carbon mass (SOCM) in differing soil taxa at 30 and 100 cm depths. These data were homogenized to U.S. Soil taxonomy based on polygons of different regional soil maps. Although the data address SOCC and SOCM to depths of 3 meters, the data for 30 and 100 cm were primarily used as surface fires (even very intense ones) are unlikely to penetrate soil layers to a depth of 3 meters. There is cross over analytical value between the shapefiles from the NCSCD and the thermokarst areas shapefile (the thermokarst shapefile uses the same SOC data as the NCSCD). Like the permafrost dataset, the primary weakness of this dataset is the lack of a temporal component to the data that inform conclusions about the rate of carbon lost due to fires annually.

The thermokarst landscape data provides the distribution of risk for topographical deformation in the boreal and tundra ecoregions within the central Alaskan region (Olefeldt et. al. 2016). These data were compared with areas of permafrost extent and NCSCD data to elucidate potential relationships between soil carbon mass or concentration and the susceptibility to surface deformation within boreal permafrost locations as caused by thermokarst. This answers the question of thermokarst's effects on carbon levels on the landscape and patch levels, and how those altered carbon contents alter regional emissions profiles. Numerical estimates based upon the best available remote sensing technology, provide a quantifiable measurement of subsided areas in the boreal landscape. Soil organic carbon (SOC) content associated with wetland, lake, and hillslope landscapes were calculated using available SOC data (30 cm and 100 cm SOC data are from the NCSCD [Olefeldt; 2016]). As with permafrost and NCSCD data, the primary weakness of these data is the lack of temporal information, so analyses conducted with these data will be a "snapshot" of the thermokarst areas as of 2015 and require assumptions of future landscape behavior.

2.1.3 Alaska Wildfire Data

Wildfire shapefiles were obtained from the United States Department of Agriculture (USDA), United States Forest Service (USFS) and from the Alaska Fire Service (USDA.gov; USFS.gov; AFS.ak.blm.gov). These shapefiles contain a multitude of data on Alaskan wildfires from 1942 until present; however, for the purposes of this paper, the fire data that were used to generate predictive map models, and geospatial analyses were data from 2000 until present. The reason for the exclusion of previous data is while the boreal region had severe wildfires recorded in the region since the 1860's when Alaska was purchased from Russia, only the records from 2000 until present can be considered of sufficient reliability to be used in this study because of a previous lack of uniform reporting procedures prior to recent decades, and possible inaccuracies in original estimations of fire areas and sizes (afsmaps.blm.gov). Current data addresses fire size by acreage, month and year of occurrence, location of occurrence, date of ignition and extinguishment, and final disposition of the fire (whether the fire developed into a "holdover" fire or was completely extinguished). Monitoring trends in burn severity data will also be used in concert with Alaska fire perimeters to analyze fire's influence on permafrost dynamics and soil carbon combustion. Although this dataset contains much of the same information as the Alaska Fire Service dataset, burn severity data will be used to evaluate trends in burn severity and help develop and assess the effectiveness of land management recommendations (mtbs.gov). This dataset will be the most useful in representing the relationship between wildfire, soil carbon emissions, and vegetative composition shift within the boreal region. This data does not contain information regarding predominant species of tree or other vegetation and biomass burned; however, shapefiles from the U.S. Forest Service do provide a limited dataset on the extent of black spruce (the most flammable forest type in the boreal region), which can be geoprocessed to support literature findings regarding fire severity and areas of black spruce dominated forest stands.

2.2 GIS Tools & Methods

More in depth analysis of the described data are required to provide quantitative insights into the relationships between soil carbon, wildfire, permafrost and thermokarst and therefore geoprocessing of the data is necessary to extrapolate information that elucidates these relationships through spatial analyses. The geospatial analyst allows data to be spatially "transformed" to better quantify spatial relationships between points, lines, or polygons of interest. This allows extracted tables and graphs of information on wildfire and its spatial relationship with soil carbon pools, permafrost, and thermokarst areas that can be statistically analyzed (using summary statistics, regression, and correlation analyses) to provide a better understanding of area values (Allen 2009). These values can be used to show a "point in time" relationship since fire polygons are the only data set with a temporal aspect. Although relationships illustrated with data are static because of the lack of temporal attributes, these data can still inform relationships that support evidentiary conclusions from reviewed literature. An explanation of the functioning and theory behind these tools will assist in making subsequent conclusions in later sections of this paper clearer, and will provide a basis for understanding how these conclusions were arrived at based on the data.

2.2.1 Clip Geoprocessing Tool

The data for thermokarst and soil carbon encompass the entire northern hemisphere of the earth and since the area of interest for this project is limited to just the boreal forest region of Alaska, the dataset requires considerable truncation, while maintaining geospatial integrity. The clip tool extracted and overlaid the desired feature class into a specified area (in this case the boreal region of Alaska). This tool cuts out a piece of one feature class using one or more of the borders in another feature class as a "cookie cutter" (Allen 2010). This is will create a new feature class—the study area or area of interest (AOI)—that contains the desired geographic perimeters (ArcGIS 10.3.1 Help). The following is a graphic illustration of the functionary process:

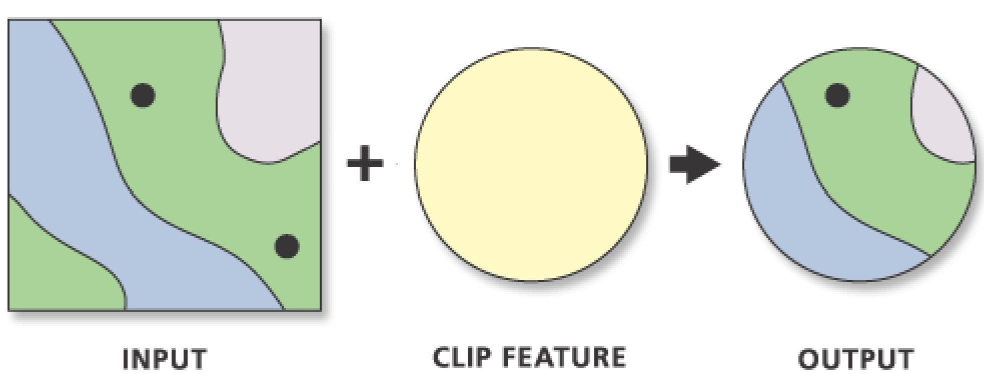


Figure 2-1: A process illustration of how the clip function transforms a shapefile consisting of points, lines, and polygons (Illustration from ArcGIS 10.3.1 help).

The clip features can be points, lines, and polygons, depending on the Input Features type. The resultant output feature class will contain all the attributes of the input features, for instance clipping the soil organic carbon (SOC) from the NCSCD to just the boreal region of Central Alaska (using the ecoregions shapefile [Figure 1-1]).

2.2.2 Intersect Geoprocessing Tool

The attributes of soil organic carbon concentration and permafrost extent are critical elements of determining the amount of total SOC concentration in the various permafrost types by region. To effectively analyze this relationship, these shapefiles had to be brought together to provide a geometric union of critical data points in a spatial relationship. This is accomplished using the intersect geoprocessing tool. This tool determines a geometric intersection of the input features, and overlapping features become part of a new output shapefile (Allen 2009; ArcGIS 10.3.1). This is represented by the following illustration:

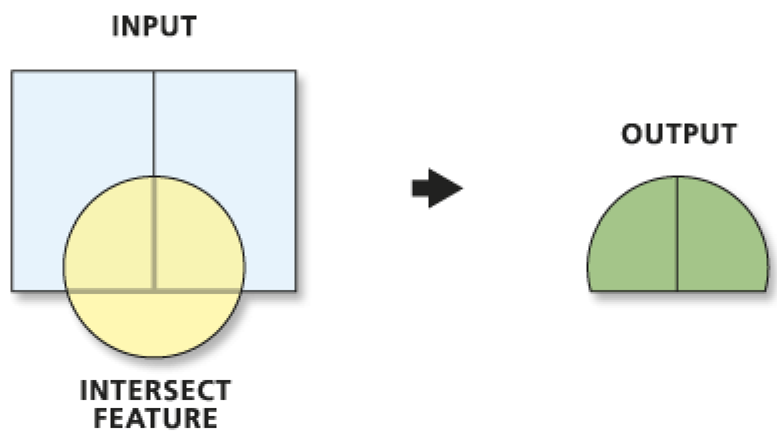


Figure 2-2: The resulting feature class from the intersect tool consists of a geometric union of the input feature classes and contains attributes of interest for analysis (image from ArcGIS 10.3.1 help).

When this tool runs, features or portions of features that overlap in the two datasets (layers) are written to the output feature class (Allen 2009). In the instance of intersecting the fire polygon with the permafrost extent polygon, the resulting feature class shows where fires have occurred within the region of permafrost extent, and creates a feature class with the necessary data to perform simple summary statistical analysis.

2.2.3 Dissolve Geoprocessing Tool

Summary statistical analysis is possible by using the dissolve tool to calculate a statistical parameter of interest against another field within the feature class. As part of the dissolve process, the aggregated features can also include summaries of any of the attributes present in the input features (Allen 2009). For example, the total amount of SOC within a specified area can be analyzed by selecting the appropriate statistical function (sum, mean, median, etc.) in comparison to the total area of discontinuous permafrost as measured in hectares. This will yield a result that shows the average SOC within all extents of permafrost areas. The dissolve tool creates a new coverage by merging adjacent polygons, lines, or regions that have the same value for a specified item (Allen 2009), and the specified fields are aggregated (dissolved) into a single feature. A multipart feature is a single feature that contains noncontiguous elements and is represented in the attribute table as one record (ArcGIS 10.3.1). The following is a graphic illustration of the functionary process:

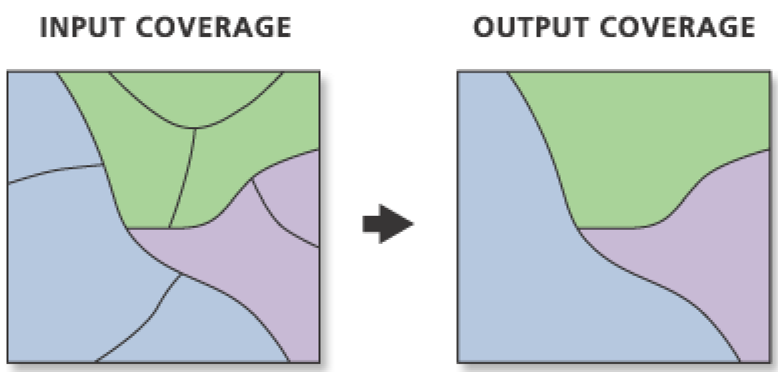


Figure 2-3: The dissolve tool process. Adjacent polygons with the same feature become one larger polygon while preserving spatial integrity of the original feature class(es) (Allen 2009; Mitchell 2009).

It should be noted that the merging of polygons with this tool is the counterpart of intersecting polygons in overlays; dissolve will remove the boundaries of the shapefiles being dissolved (ArcGIS 10.3.1). Also, while the input coverage may contain information concerning many feature attributes, the output coverage contains information only about the dissolved item (ArcGIS 10.3.1). This is the tool I used to conduct my primary analyses of soil carbon concentrations within permafrost areas and thermokarst areas, and to determine the locations and sizes of wildfires by year and acreage within these same areas to determine fire’s influence on these phenomena. This tool will also provide analytical data on the relationship between soil carbon and wildfires, elucidating those areas of greatest carbon concentration in relation to the largest wildfires as defined by GIS acres (the GIS acres is a more accurate measurement of fire size as it comes primarily from LANDSAT data).

Where datasets lack certain analytically essential attributes (like soil carbon concentration in a certain unit of area), fields can be added to these datasets that can show the desired information. Creating a new field and using the appropriate mathematical or systemic operators allows for information to be either collated from different attributes within the data table or concatenated to extract a specific value. This adds additional fields based on simple calculations to existing shapefiles that contain more precise data that useful to conducting analyses. Simple geoprocessing tools will create the necessary data tables to determine what variables are independent and which are dependent. These GIS processes and datasets provide supporting analyses to strengthen the evidence propagated from the literature that discuss the complex interrelationships of climate, fire, soil carbon, and resultant increased carbon emissions that are the chief consequence of a longer more aggressive fire season. The literature synthesis and geospatial analyses used to answer the central question of climate's effect on fire activity and resulting carbon emissions are outlined in the following evidence section.

Section 3.0- Evidence

3.1 Soil Carbon Dynamics

Soil organic carbon (SOC) as defined in the literature is the layer of organic carbon found within soil strata due to deposition of plant and animal residues, root exudates, living and dead microbial organisms, and miscellaneous soil biota (Hugelius et. al. 2013; USDA 1999). There are two main pools of terrestrial carbon in the boreal region: vegetative biomass (trees, shrubs, grasses) and surface soils (near surface horizons with decomposable detritus stocks) (McGuire et. al. 2009). Soil carbon cycling is a function of soil nutrients, horizon profiles, temperature, and hydrologic capacity and is interlinked to permafrost dynamics (Jorgenson et. al. 2015). Generally, the upper 1 m of soil stores as much as 14-1600 PgC throughout the Arctic regions and up to 2400 PgC at a depth of 2 m cumulatively (McGuire, 2009; Hugelius, 2013). Soils in tundra and boreal forest regions hold as much as twice the amount carbon present in the atmosphere in depths of 1-2 m (Bret-Harte et. al. 2013), and soil types determine the level of carbon storage (Table 3 in Appendix A). To understand the carbon storage capacity of regional soil taxa, and how topography, fire cycles, and climate changes influence regional carbon storage capacity (and thus emissions because of disturbances in these influences), it is necessary to support literature findings with GIS data to elucidate the larger, interconnected relationship these factors have with soil organic carbon stocks. It should be noted that for soil analyses using ArcGIS software®, the data collected and compiled was published in 2013, and as stated in Methods Section 2.0, there is no temporal factor. Therefore, to establish relationships between the changes in the quantity of soil carbon and area, and relationships between other independent variables such as fire (acreage), permafrost extent, and thermokarst, an assumption must be made that regional soil carbon concentrations (MgC Ha^{-1}) do not drastically fluctuate over short intervals of time (decadal periods or less).

Soil Taxa and Carbon Storage Characteristics

Soil taxa is a determining factor in regional SOC storage capacity, and although there are many cryogenically influenced soil taxa, three soil types prevalent in the region store the greatest mass of carbon (Figure 3-1).

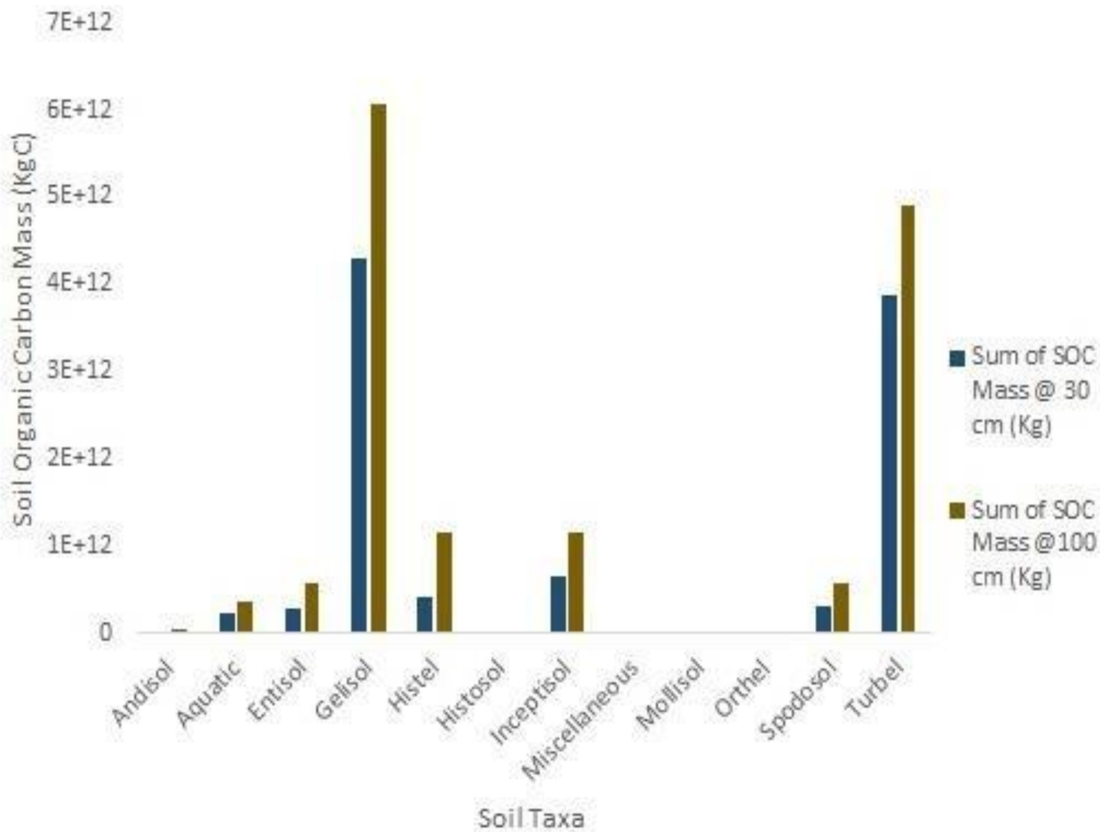


Figure 3-1: Soil taxa by depth and the quantity of SOC stored therein. Gelisol, Turbel, and Inceptisol soils at 30 cm (blue bars) and 100 cm (brown bars) store the greatest quantities of regional soil carbon in Kg. Data extrapolated from ArcGIS® geoprocessing of the Northern Circumpolar Soil Carbon Database (NCSCD) as compiled from Hugelius et. al. 2013.

Turbel and gelisol soil types are the most abundant soil species within this region and are defined by the greatest carbon storage potential (Jain et. al. 2012). Gelisol type soils are found throughout the boreal region (Figure 3-2) and are defined by their unique attribute in that they are formed by the processes of freezing and thawing and almost always have well defined permafrost layers (USDA 1999). The freezing and thawing processes produce granular and vesicular structures (fine grains marked by pockets within the grains themselves) throughout the soil horizon layers,

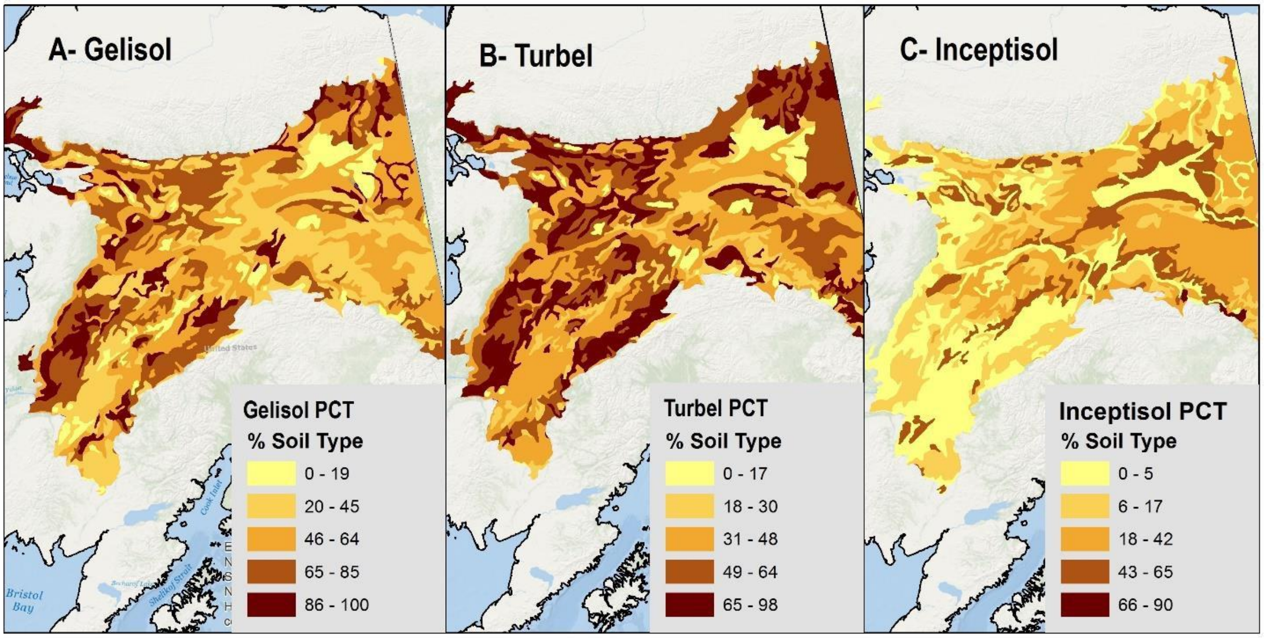


Figure 3-2: The three predominant soil taxa by percent of the total soil composition that are within the boreal region by percent composition of the total soil matrix (Hugelius, 2013).

And these soils pool large carbon stocks particularly near the permafrost interface. The second most prevalent species of soil is turbel soils. Turbel soil types (Figure 3-2) are the most dominant sub-species of gelisol soils and exhibit many of the same characteristics of gelisol soils; they have broken or irregularly defined horizon layers (a result of freezing and thawing cycles), they store stocks of soil carbon in near permafrost layers, and they are composed of similar granular composition and size (USDA 1999). Additionally, this dominant suborder of gelisols accounts for almost half of global gelisol soil mass (USDA 1999) and thus composes a considerable portion of the Alaskan boreal regions soil profile. The primary difference between turbels and gelisols is that turbels do not have SOC stocks that are saturated for more than 30 (continuous) days a year and have 80% or more, by volume, organic soil materials from the soil surface to a depth of 50 cm (USDA 1999). Both soil species have considerable carbon storage capacity and the larger granule size of turbels (coupled with interspersed rock) means this soil species stores more water throughout the horizon layers and forms ice wedges that can preserve permafrost (O'Donnell et. al. 2011; Jorgenson et. al. 2015). Inceptisol soils (Figure 3-2) in the Alaska boreal region are glacially formed soils and occur in areas of young and old deposit (USDA 1999). These mineral soils are common in unfrozen areas and do not have permafrost within 100 cm of the surface. This type of soil is defined by clear demarcations of soil horizons and higher clay, metal oxide, and minor humus content but not of a sufficient quantity to fall into other soil taxa (USDA 1999). It is porous and so nutrient loading (primarily carbon and nitrogen in this region) tends to occur in denser layers where appropriate levels of drainage can occur. This nutrient loading is contingent upon adequate drainage, if drainage is impeded then the SOC loading cycle can be negatively affected resulting in localized or regional effects to carbon dynamics (Bond-Lamberty et. al. 2007). The result is that these soils have a capacity to store large amounts of carbon and nutrients that resists decomposition (near the permafrost interface) due to lower temperatures that cryogenically preserve carbon stocks (O'Donnell et. al. 2011). In total these soil carbon reserves compose over 352,000 km^2 of the boreal forest region (data processed from NCSCD in ArcGIS®). Gelisol soils compose the largest species of soil type throughout the region at both 30 and 100 cm below ground surface, and show a wide spatial distribution that correlates with major interior rivers (that transport large amounts of organic material during spring thaws [Hugelius et. al. 2013]). Given the range and volume of these soil types, more aggressive fire regimes can release considerably more carbon emissions. Where stand replacing fires occur, these areas become carbon sources, however, if the fire return interval is of sufficient length (>200-300 years) within 10-20 years these areas can once again become carbon sinks (Amiro et. al. 2010).

Climate Influences to Soil

Average ground temperatures within the circumpolar region and in the boreal forest of Alaska has increased over the last 30 years (Harden et al. 2000; Wendler & Shulsky 2009) thus soil carbon stocks in upper soil horizons are may become vulnerable to combustion as fire regimes change in concert with rising temperatures. Tundra soils are less susceptible to soil warming than boreal regions (Jiang et. al. 2015) and this is largely due to the buildup of ground level vegetation that forms an insulating layer. The surface detritus layer in boreal regions largely consists of downed leaves or conifer needles with ground level vegetation being more sporadic based upon the shading from large forest stands (with greater fire susceptibility as these layers accumulate or dry out [Harden et. al. 2000; Balshi et. al. 2009]). Alaskan circumpolar soils are characterized by high concentrations of soil carbon (Figure 4 in Appendix A) formed by organic matter deposition over time that deposit in soil taxa and are preserved by the colder soil temperatures prevalent in the region.

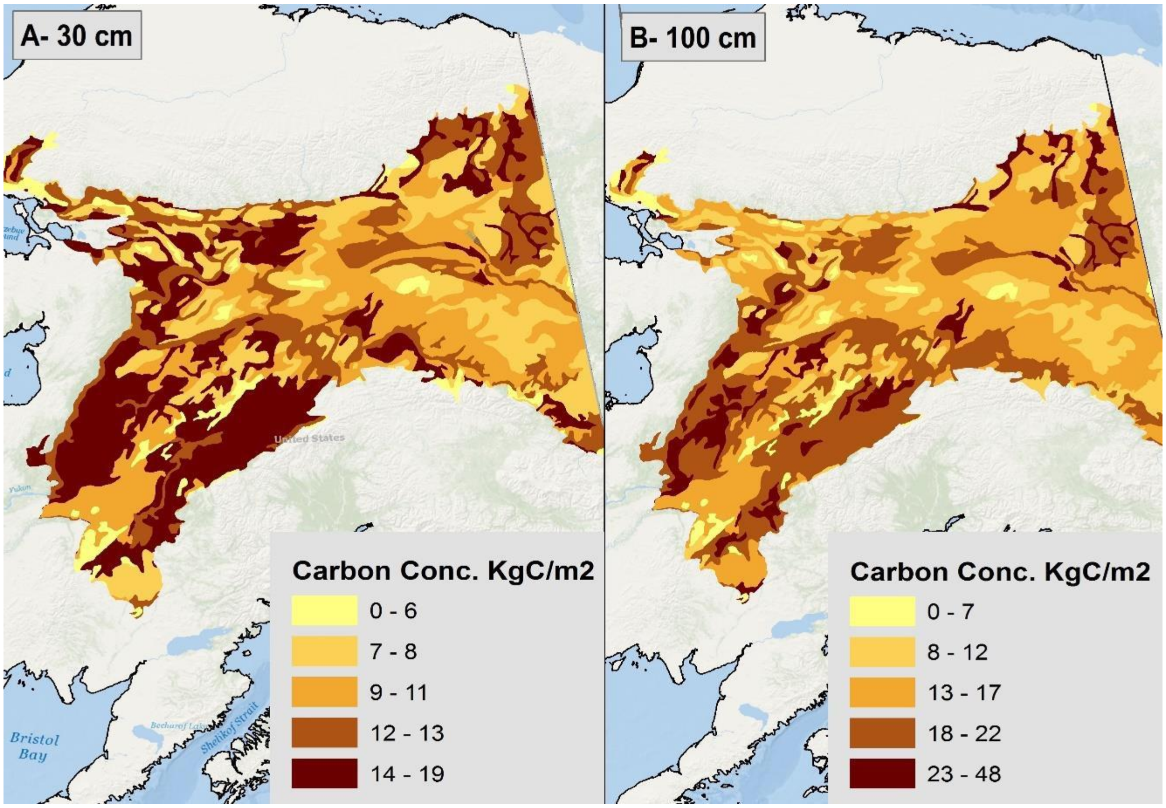


Figure 3-3: Soil organic carbon concentrations in the boreal region showing concentrations at (a) 30 cm depth and (b) 100 cm depth. Data compiled from the NCSCD Hugelius et. al. 2013.

Soil carbon concentrations within the boreal forest region increase between depths of 30 and 100 cm (Figure 3-3) and despite their depth, carbon stocks at 100 cm are vulnerable to increased fire activity and can be particularly problematic as this depth fosters holdover fires (Alaska Interagency Fire Management Plan 2016) that smolder below ground and reignite to become ground level fires under the right conditions. Forest and tundra landscapes often border or intermingle, and climate changes are increasing this connectivity resulting in linked carbon pools that are more vulnerable to fire influences (Turetsky et. al. 2014). Tundra landscapes tend to be dominated by a pronounced peat layer (Harden et. al. 2000) and when these layers form edges with boreal regions, they become hotspots for soil carbon build up, and an interface for the transition of forest fires into tundra fires.

When soil layers warm increased microbial activity tends to occur with a subsequent reduction in near surface soil carbon levels (Boby et. al. 2010). Warming soils tend to lose trapped moisture from the hydrologic column due to evapotranspiration (Euskirchen et. al.

2008); evaporation results in drier near surface carbon layers that oxygen can readily circulate through. The density of these soils decreases with a loss of moisture trapping organic material (Trugman et. al. 2016) which increases both aerobic, and at deeper layers, anaerobic respiration with resultant increased GHG release (Boby 2010; Taş et. al. 2014). The carbon stocks in microbe rich layers are a favorable medium since soils are no longer water logged and are now aerobic or near aerobic environments rich in carbon based nutrients that support continued microbial activity (Tamocai et. al. 2009). As microbes decompose newly available organic material, they reduce the amount of carbon in near surface layers that results in greater areas of mineral soils being exposed (Boby et al. 2010). This cycle becomes a more pronounced self-sustaining positive feedback loop if temperatures stay elevated over historic averages.

As climate trends toward warming, deeper soil layers will become more significant to regional carbon cycling (Ping; 2008). Retreating permafrost increases the amounts of available soil nutrients releasing previously frozen nutrient stocks into the soil improving growing quality of near surface soil layers (Trugman et. al. 2016; Mack et. al. 2004). When this occurs, surficial biomass increases in the presence of greater quantities of limiting nutrients. Additionally, mild fires (of low to moderate intensity) defined by longer return interval favor decreased decomposition (Trugman; 2016) by removing less surface organic material and temporarily aerating soil strata by drying surface soils. Mild fires fix key nutrients (such as N_2) in the upper soil horizons contributing to a feedback loop of greater biomass density with a subsequent preservation of stable permafrost and soil carbon (Balshi et. al. 2009). Ultimately, soil organic layers stabilize because of increased nitrogen that supports SOC accumulation due to increased surface biomass—these layers when sufficiently dense act like "sponges" that hold moisture and nutrient pools in the growing organic horizons of soil layers (Boby et. al. 2010) and can phlegmatize future ground fires.

Mean regional temperatures and precipitation (both in rain and snowfall) along with soil types, distribution, and organic carbon concentration influence soil vulnerability to combustion during fires. Climatic influences of decreased rainfall during summer months contributes to stocks of unusually dry surface biomass that is more vulnerable to ignition from lightning strikes during frequent thunderstorms during late spring and early summer (Jiang et. al. 2015). During years where heavy snowfall has occurred, and spring rainfall levels are above average, soil carbon layers are protected from fire damage because the increased moisture results in saturation of upper soil layers and dense biomass secures soil integrity by its interlocking and dense root systems (Norris et. al. 2010). Under these conditions SOC and biomass loss can be minimized since wet vegetation does not generally burn, and tree mortality is reduced. Damp soils with dense biomass also reduce the fire return interval (Jain et. al. 2012), and as previously stated, low to moderate intensity fires with longer return intervals favor nutrient loading in the soil that supports sustained forest health. This increase in biomass stabilizes the regional carbon cycle until the fuel load gets sufficiently large to be at risk to wide scale loss by large fires.

Topographical Influences on Soil Carbon Dynamics

The topography of the boreal forest region is defined by low sloping mountains of lower altitude than the Alaska range on the southern border of the region or the Brooks Range in the northern portion of the boreal region. This topography is favorable to soil carbon accumulation in that low-lying areas generally allow for settling of surface carbon (Turetsky et. al. 2014). Using data from Hugelius (2013) and the NCSCD, regression analysis shows that soil organic carbon concentrations, both at 30 and 100 cm, show no correlation with area ($SOCC_{30cm}$; r^2= 0.000652, p= 0.442; $SOCC_{100cm}$; r^2= 0.0010 p= 0.321) therefore other factors (soil type, topography, vegetative over story) must determine carbon deposition dynamics that influence carbon concentrations at 30 and 100 cm depth. Several large rivers run through the boreal region; The Yukon, Tanana, and Nenana rivers whose volumes can double during the spring “break up” season when melting snow and ice temporarily increase river levels and transport large amounts of organic material to shoreline areas as they flow (Tan et. al. 2007; Ding et. al. 2014). This region is composed of exclusively forest and tundra—and the reviewed literature agrees that these landscapes are a consistent and nearly constant source of organic materials that convert to carbon stocks in upper soil horizons that migrate to lower soil strata over time (Jones et. al. 2005). This results in some low-lying areas having very rich stocks of labile soil carbon that serve as fuel under altered fire regimes and seasonal shifts. This finding from the GIS data supports the findings of the literature that states the northern permafrost regions store the greatest global quantities of carbon (Tamocai et. al. 2009; Norris et. al. 2010; and others), and the largest stock of carbon in Alaska.

Landscape is a critical to determining factors of SOC storage capacity and much of the literature indicates that topography is a determining factor of carbon concentration. Areas of higher elevation will tend to have lower concentrations than low lying areas due to the less favorable growing conditions at higher altitudes that do not support dense surface biomass, the leading contributor to soil carbon stocks. Rocky and rubble dominated soil profiles store less SOC than low lying areas or foothill regions (Ping et. al. 2008; Jorgensen, 2015). Existing soil carbon layers in mountainous areas take much longer to replace when they are lost to fire, because these landscapes are sparsely populated with vegetation, and forest stands do not exist above the alpine barrier. Lower lying areas defined by finer grained soils store considerable amounts of SOC and in upper horizons (20-40 cm of depth [Ping; 2008]) and are at greater risk to wildfire removal of upper layer carbon. Areas dominated by coarser sand sized soil particles contain higher quantities of labile soil carbon characterized by more rapid turnover rates (Norris et. al 2010). These areas also store more limiting nutrients (such as nitrogen) that foster the growth of dense biomass that under increasingly drier and warmer conditions become a larger pool of fuel.

Bolshi and fellow researchers (2009) proved that spatial distribution of soil carbon concentrations were a product of wildfire activity. O'Donnell and fellow researchers (2009) showed that vegetative composition at the surface affected near surface soil horizon's stocks of labile soil carbon. Areas where dense grasses and mosses are intermingled with forest stands contribute greater volumes of SOC that builds up and forms dense concentrations of soil carbon (Pieters et. al. 2011). Areas that are dominated by grasses and shrubs tend to be better drained soils that allow for soil carbon stocks to diluted or spread out to larger areas (Norris et. al. 2011). Heavily forested areas will store the most soil carbon and thus result in pools of high carbon concentration because tree root systems form stabilizing subsurface networks that slow water migration and stabilize extant SOC layers (Norris 2011). Given a constant value of carbon input and increased soil drainage, these factors would contribute to lower carbon concentration in spatial distributions (Ding et. al 2014). The data appear to confirm literature findings regarding carbon concentration; areas within the boreal region tend to pool carbon and it is these areas that are at the greatest risk of becoming net carbon sources during more intense and frequent fires.

Spatial variability of soil carbon content influences regional fire cycles by providing an additional pool of fuel to flammable above ground biomass stocks (McGuire et. al. 2009). This factor does not necessarily influence fire behavior since ignition takes place at the surface and biomass provides the initial fuel source (McKenzie et. al. 2004). The influence soil carbon exerts on fire is secondary—it merely adds additional fuel for fires once they begin, and in this way SOC concentration is not entirely neutral in its relationship to wildfire. Fire influences SOC concentrations and these pools exert influence on fire regimes through greenhouse gas (GHG) outputs that support positive feedback loops (Liu 2014). Areas of deciduous dominant forest stands tend to have higher soil carbon concentrations (B. Young et. al 2016) and coupled with above ground biomass exert patch and landscape level influences on fire (Johnstone et. al. 2010).

3.2 Permafrost Dynamics

Permafrost dynamics influence soil carbon stocks, landscape transformation, and surface vegetation composition; the complex feedbacks between these factors are what ultimately influences the rate of increased regional carbon emissions as regional mean temperatures warm.

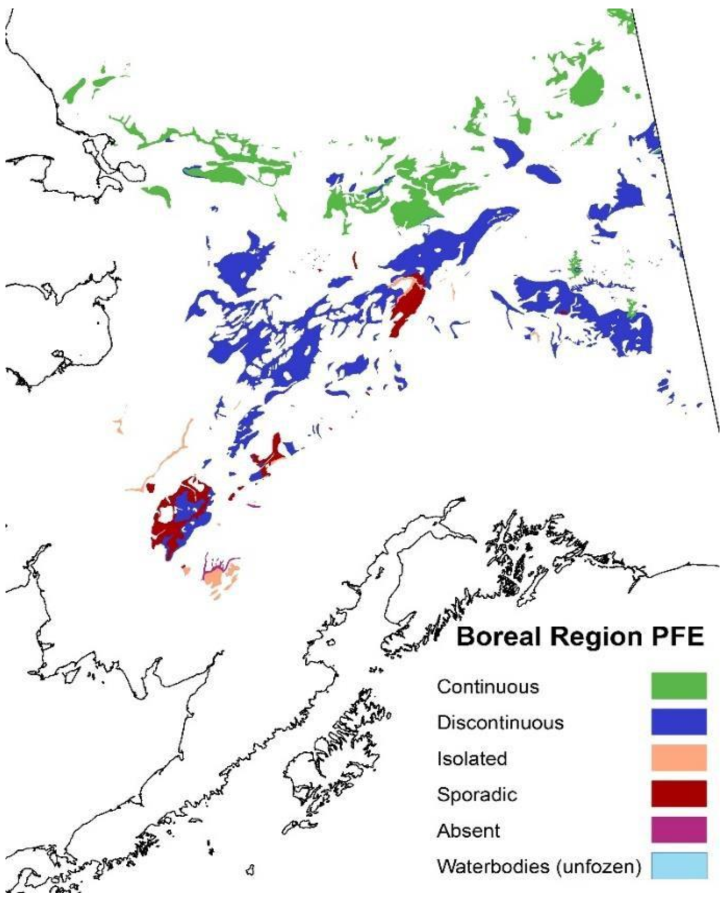


Figure 3-4: Alaska permafrost extent in the boreal region based on data from Jorgensen et. al. 2008.

Permafrost layers underlie considerable tracts of boreal landscapes (Figure 3-4) and sequester vast amounts of soil carbon (Figure 3-6, Table 1 Appendix A); as much as 18.8 kg/m^2 at 30 cm of depth and up to 48.2 kg/m^2 at 100 cm of depth (Hugelius et. al. 2013). Thawing of permafrost in these areas activates dormant carbon rich soil layers (Lawrence and Slater 2005), making them more susceptible to combustion as temperatures warm and drive longer, aggressive fire seasons. When the permafrost layers thaw, carbon loss can be 30 ±20% (Jones et. al. 2016) of the initial forest carbon stocks. Using CCSM3 (that analyzes hydro thermal frozen soil profiles) and CLM3 (that uses a layer deep snow pack model sitting atop a 3.43 m deep soil horizon model) run against SRES A1 (high) and B1 (low) GHG emissions scenarios, Lawrence and Slater (2005) demonstrated that if current climatic trends continue unabated, by the year 2100, considerable quantities of permafrost could be lost

(Figure 7, Appendix A). As regional ground temperatures trend toward increase (Figure 3-13), and when compared to the current regional permafrost extents, it is likely that permafrost degradation will continue through the end of the century.

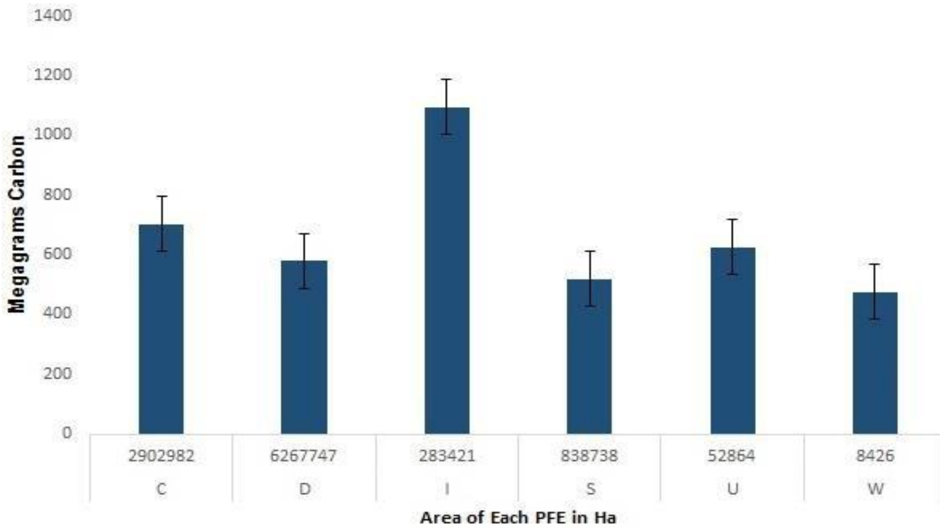


Figure 3-5: MgC in each permafrost class delineated by the area in hectares for each permafrost category as defined by Jorgensen et. al. 2008. In this figure permafrost extents are C- continuous, D- discontinuous, I- isolated, S- sporadic, U- permafrost absent, and W- large waterbodies (unfrozen). Areas of isolated permafrost store the greatest amount of carbon, most likely due to seasonal thawing in neighboring soil horizons that allows for decomposition of organic material to occur. Data from NCSCD (Hugelius, 2013) and geoprocessed with ArcGIS® software.

Multi-year and multi decadal trends in climatic patterns determine the susceptibility of permafrost layers to thaw and collapse (Brown et. al. 2015). Earlier, warmer summers drive more aggressive and deeper permafrost retreat within the boreal region (Lara et. al. 2016). While the levels of decline differentiate based on topographical influences (areas of higher elevation tend to be less susceptible than low lying landscapes) the overall trend is one of permafrost layers retreating to deeper soil horizons, increasing labile carbon stocks (Brown et. al. 2016), and contributing to topographic alteration because of thermokarst processes (Davidson & Janssens 2006). It is worthy of note that as labile carbon stocks increase, they contribute to increased fuel loads at greater risk of combustion during novel fire regimes and the radiative forcing from ground level fires accelerates thermokarst processes (Brown 2016). Isolated permafrost extents (40% permafrost soils or less) areas constitute the smallest permafrost extent by regional area, but store the most organic soil carbon by mass in megagrams carbon per hectare (Figures 3-5 & 3-6). Continuous and discontinuous areas constitute the largest extents, but store only half to three quarters the volume of carbon. The northern edges of the boreal region, where permafrost is classified as nearly continuous throughout the range, contain concentrations of SOC ranging from 500 to 700 MgC/Ha, which indicates that these areas could be at a lower risk of thermokarst processes than isolated permafrost extents, but even though these areas have a net lower quantity of SOC in comparison to isolated permafrost areas, they constitute nearly 2 orders of magnitude more surface area in the region (188% more land area in hectares), and therefore thermokarst as a product of soil carbon concentration (Olefeldt et. al. 2016) and fires in isolated permafrost extents are likely to have a greater impact to carbon stores and thus future emissions.

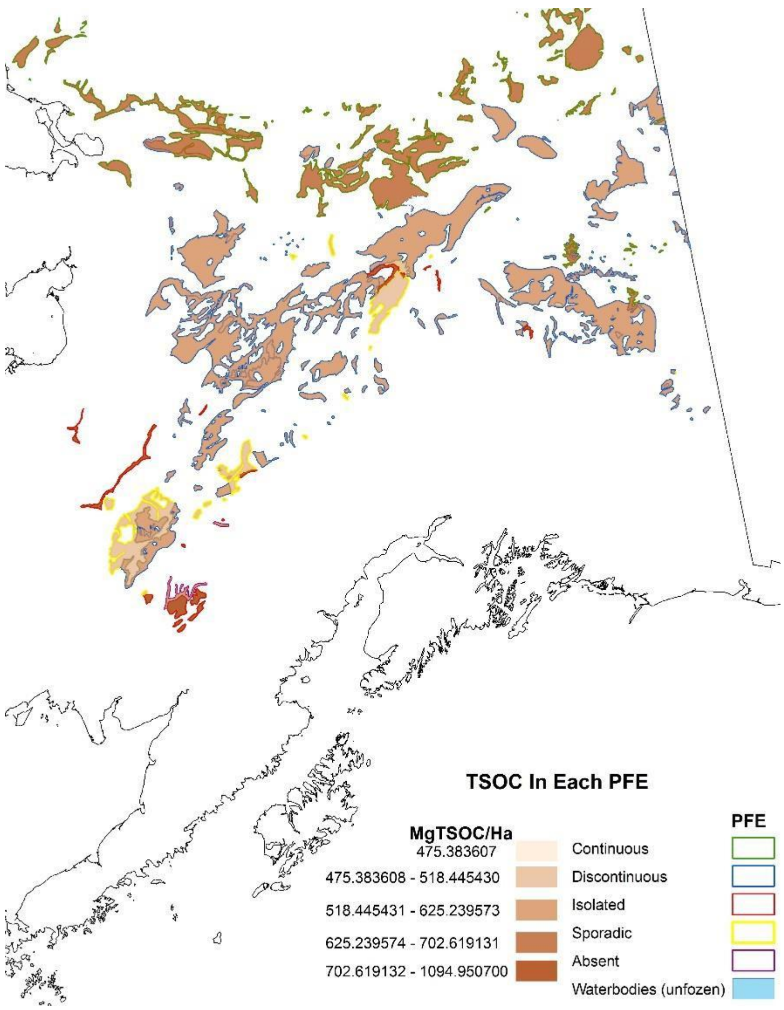


Figure 3-6: Extents of permafrost and quantities of SOC by mass in megagrams in each extent of the boreal region. Note the greatest amounts of carbon sequestered in continuous and discontinuous permafrost, although high carbon quantities may be found in patches of isolated and sporadic (40% or less) permafrost extents due to topographical influences. Data compiled from Hugelius et. al. 2013 and Jorgensen et. al. 2008.

Fires of sufficient intensity eliminate insulating carbon layers (Taş, 2014) and although low intensity fires may result in ecosystem recovery to full pre-fire condition (Lorianty et. al. 2014) large severe wildfires can favor a decline of permafrost (Brown et. al. 2016) on the patch and landscape scale that opens new stocks of previously cryopreserved carbon. Peatlands (muskeg and similar landscape profiles) are often found on the edges of boreal forests or are interspersed as patches throughout boreal forest landscapes (Jones, 2016). These areas serve as net carbon sinks as biomass detritus in the form of dead grasses, leaves, or conifer needles accumulate in these areas over time.

Cold ground temperatures slow decomposition rates, cryogenically sequestering source material within the soil layers, until those layers are exposed through warming temperatures. Recession of the permafrost changes the microbial content and activity of regional soils

(Neslihan et. al. 2014), which in turn alters biogeochemical soil processes such as decomposition resulting in increased methane (CH_4) output from areas previously defined as carbon sinks. Permafrost retreat influences how quickly organic carbon rich layers regenerate or recover post wildfire (O'Donnell et. al. 2011). These researchers found that active layers (soil layers above permafrost that freeze and thaw annually) and organic horizon thickness (layer of organic material in near surface soil horizons) was strongly influenced (on patch and landscape scales) by surface combustion from wildfire (r^2= 0.79, P= 0.0029). While the permafrost layer, characterized by the slowest turnover rate (>3000 years), showed little influence from even more severe fires in the immediate term (O'Donnell; 2011). Given the generally slow rate of layer recovery following severe fires, these new layers will be more susceptible to carbon content loss from increased fire activity.

Permafrost Recovery Capacity

While fire exerts strong influences on permafrost and carbon levels on patch and landscape scales and climate tends to exert regional influences, the permafrost layers may not be as vulnerable to these forces as research initially suggests. Plant growth and increased net primary production (NPP) may offset carbon losses (Schuur et. al. 2009) as mineral soil horizons exposed by receding permafrost and fires creates favorable conditions for increased deciduous biomass. Denser, more abundant vegetation may tilt the carbon balance of these regions back toward the status of a carbon sink, if NPP rates can increase by an average of 14% annually over present NPP rates to compensate for the carbon lost to fire activity and present rates of permafrost decline (O'Donnell, 2011). As permafrost retreats it alters the soil moisture and drainage patterns of overlaying soil horizons (Lawrence & Slater 2005) which alters soil moisture content, causing soils can become drier. Surface water pools that previously could not migrate into lower soil horizons and deeper aquifers may find new drainage pathways as retreated permafrost allows water to percolate further down into soil strata than it previously could under antecedent climatic conditions (Lawrence & Slater 2005). Increased hydrologic conductivity alters vegetative composition (Routh et. al. 2013), which results in greater regional carbon stocks over time through buildup of either dead or desiccated surface biomass. Altered vegetative composition translates into plant detritus composition changes as areas previously dominated by shrubs, grasses, and muskeg transform into favorable habitat for coniferous and deciduous tree species (Shenoy et. al. 2010). Overall these processes contribute to a regeneration of the insulating organic carbon layer that fosters permafrost stabilization and eventual recovery (Taş 2014; Jorgenson et. al. 2015).

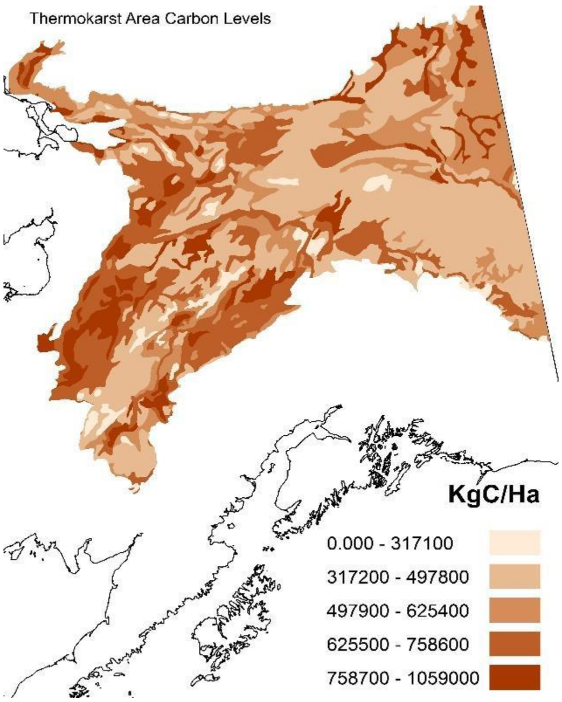


Figure 3-7: Thermokarst areas of the boreal region of Alaska. Areas of higher concentrations of subsurface organic carbon are areas where thermokarst has occurred or is likely to occur in the future. While thermokarst is generally caused by climatic influences, the processes tend to favor pooling of carbon stocks in subsided areas. Data compiled from Olefeldt et. al. 2016.

Thermokarst Effects on Topography and Carbon Cycling

Increasing average summer temperatures exert the dominant effect on permafrost retreat (regionally), and thus surficial ecosystem changes that may contribute toward increased intensity and shorter return intervals in regional wildfire regimes. This initiates a process called thermokarst that transforms surficial topography of boreal forest and adjacent tundra or peatland landscapes (Lara et. al. 2016). This process is critical because aside from altering topography and soil hydrology, it contributes directly to carbon cycling by altering vegetation profiles (Brown et. al. 2015). Thermokarst changes ecosystem function and services by altering surface biomass composition (Lara 2016). Landscapes that were previously dominated by boreal forest, a mix of boreal forest and deciduous biomass, or forest and tundra can be transformed into bogs known as muskeg (Figure 3, Appendix A), with a near total change in biomass profiles (Lara et. al. 2016; Jorgensen et. al. 2015). Thermokarst induced topographic changes influence regional fire vulnerability, with some areas being more susceptible to large, severe wildfires when they were relatively devoid of such previous fire activity pre-deformation. Fire's influence on permafrost has been noted by Brown (2015) to cause up to 0.6 m loss of ice rich permafrost in a season however this loss is on patch and smaller scale landscapes. Subsequently, permafrost may become highly vulnerable to localized collapse due to novelty in decadal fire cycles (Brown; 2015).

Wide scale thermokarst processes are largely climatically induced since it is climate that affects permafrost on the regional scale (Routh et. al. 2016). Thermokarst associated with permafrost retreat tends to cause localized topographical alterations; large scale surface deformations are rare (Liu et al. 2014) although such transformations do occur with top-down permafrost thawing (Liu, 2014). When permafrost layers retreat sufficiently, overburden soil layers subside from the lack of frost borne heaving that occurs with deep permafrost layers (Olefeldt et. al. 2016). Surface subsidence is a more comprehensive indicator of impacts to ice rich permafrost than active layer thickness alone (Jorgenson et. al. 2015). Initial thermokarst events cause the formation of troughs that fill with water and can become gullies or create a surface that is marked by hummocks. Initially, these surface malformations affect regional albedo (pooled liquid water absorbs more solar radiation than ice covered water bodies or snow) and alters radiative forcing that can put greater pressure on vulnerable permafrost layers. The net result of thermokarst processes is to create concentration pools of carbon in patches around landscapes thus altering the regional fire induced carbon emissions as the process progresses (Lara et. al. 2016). A spatial analysis of thermokarst with respect to permafrost and soil carbon concentrations reveals that thermokarst landscapes are associated with large stocks of below ground carbon (Figure 3-7) created from organic material buildup when surface patches subside.

Considerable surface transformation may occur in regions overlying continuous permafrost and discontinuous permafrost extents should the permafrost retreat that initiates thermokarst continue (Jorgenson et. al. 2008). Thermokarst surface deformation negatively affects forest health (Lara 2016) causing tree stands to become unstable. As surfaces heave or subside (Jorgenson 2015), these areas become unstable for forest stands growing in thermokarst areas (Bond-Lamberty et. al. 2014). The result is higher tree mortality due to thermokarst induced felling; this results in buildup of dead and down materials (O'Donnell et. al. 2011) that increase fire hazard risk (Bachelet et. al. 2005), despite the area's transformation into a wetland or semi-wetland (Brown et. al. 2015). This process can transform biomass composition to those species best adapted to wetter environments, and have considerable effects on the carbon cycling profile of the region (Jones, 2016). Additionally, such a transformation can result in a metabolic shift among native soil bacteria that further alters the carbon cycle (Neslihan, 2014) toward greater carbon output as landscape methane production may increase. While these landscapes may be initially less fire prone, and thus minimal sources of carbon, enhanced decomposition results in a net zero sum gain for these landscapes (Lara, 2016).

Landscape position plays a crucial role in thermokarst transformation processes that result in a collapse scar bog or muskeg dominated landscape. Spatial distribution of thermokarst in higher elevation areas alters soil drainage profiles, making thermokarst areas more susceptible to long-term soil drying and prone to widespread intense wildfires (Lara; 2016). Altering soil drainage profiles fosters shifts biomass composition by altering nutrient distribution and cycling within a patch or the landscape (Lara, 2016), an alteration that can have long term consequences for fire regimes. Although 13% of the boreal forest region of Alaska is susceptible to collapse (Lara, 2016), low lying areas are much more likely to become thermokarst landscapes (Olefeldt; 2016; Jorgensen; 2015) as average summer temperatures rise. Mountainous regions are at the least risk of thermokarst induced landscape change. Wetland and lake terrains are more susceptible to thermokarst per Olefeldt (2016) and lake and wetland areas are most susceptible to thermokarst processes based on carbon concentrations (Figure 3-8). Areas that are underlain by continuous and discontinuous permafrost are most vulnerable to thermokarst processes (Table 3-1).

Table 3-1: Permafrost extents and the likelihood of areas in wetland, lake, and hillslope terrain to lose topographical integrity due to thermokarst. Total SOC in Kg/Ha is included to show what areas could become carbon sources as in lake and wetland terrain should thermokarst surface deformation alter surficial biomass profiles. Areas of high probability with large pools of nascent carbon represent the greatest probability of becoming a carbon source as climate change increases the likelihood of large scale fires in these areas. Data from Olefeldt et. al. 2016.

Permafrost Extent	Permafrost Area (Ha)	Wetland Terrain Thermokarst Probability	Lake Terrain Thermokarst Probability	Hillslope Terrain Thermokarst Probability
Continuous	2,903,200	High- Very High	High- Very High	High- None
Discontinuous	6,268,170	High- Very High	High- Very High	High- None
Isolated	283,440	High- Very High	High- None	Low- None
Sporadic	838,792	High- Very High	High- None	Low- None
Absent	52,867	Low- Very High	Low- None	Low- None
Waterbodies (Large, Unfrozen)	8,427	High- Low	Low- None	Low- None

Loss of Organic Soil Layers Effect on Permafrost and Ecological Recovery Processes

Although thermokarst processes can result in water logged soils (when muskeg or collapse scar bogs form), in some locations layers of soil organic carbon are at greater risk of desiccation as permafrost levels decline (without thermokarst occurrence) and mean summer temperatures rise (Ping et. al 2008). Continued warming dries these layers (Brown et. al. 2016) making them more vulnerable to combustion that reduces these layers' depth and insulating

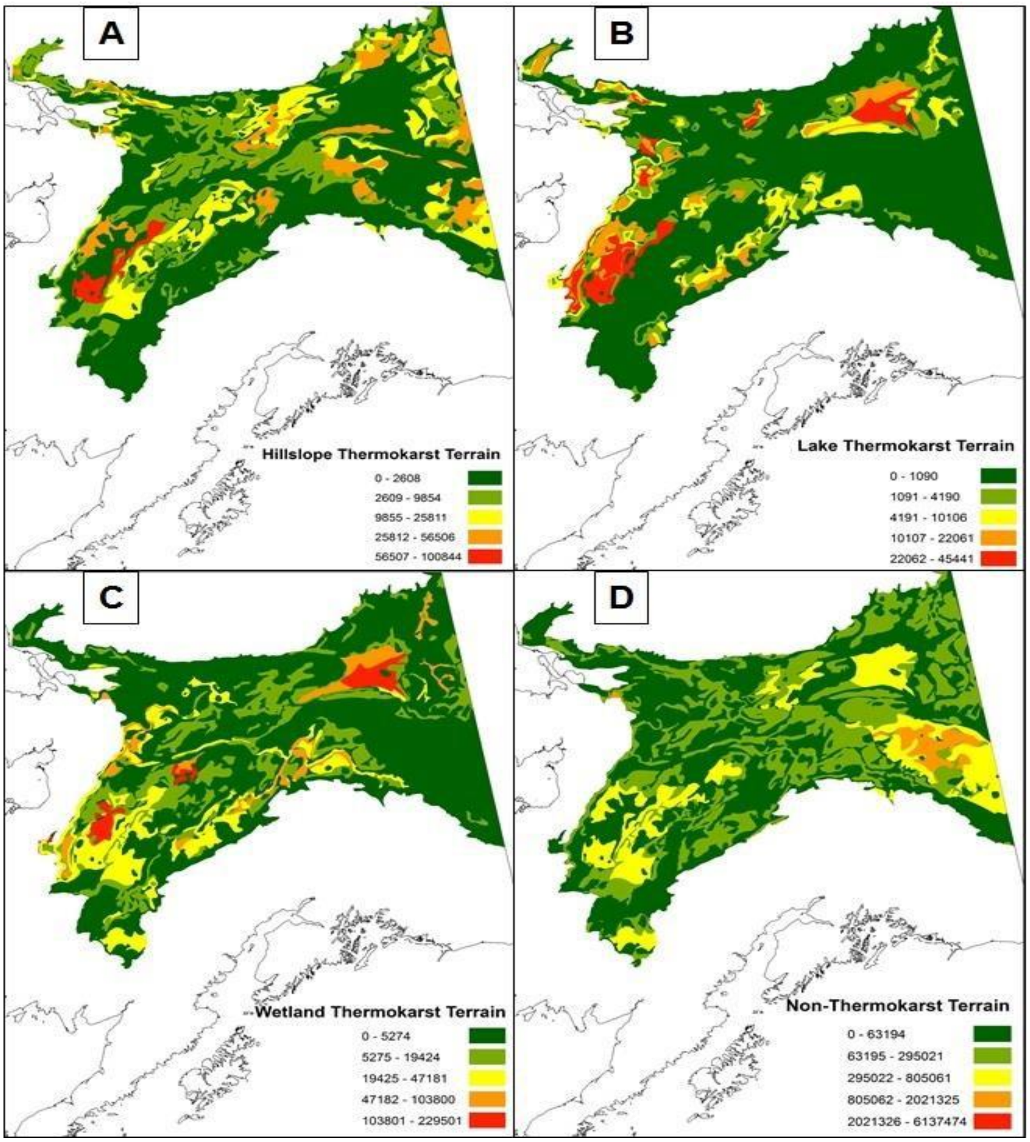


Figure 3-8: Terrain profiles and carbon concentrations (low- green to high- red) throughout the boreal region: (a) Hillslope terrain exhibiting low carbon mass along the northern and southern edges of the region—these locations correspond with the foothills of the Brooks Range (N) and the Alaska Range (S). (b) Lake terrain region thermokarst areas and SOC mass; soils that underlay permanently frozen or seasonally unfrozen waterbodies were not surveyed as part of Olefeldt's study (2016) which explains the large areas of seemingly low organic carbon mass. (c) Wetland terrain thermokarst areas, the bulk of the SOC mass in this region corresponds with the large wetland area in the Innoko National Wildlife Refuge in the SW portion of the boreal region. (d) Non-thermokarst areas—areas of little to no surface

capacity. The importance of the insulating soil organic carbon layer cannot be overstated since these layers can take thousands to tens-of-thousands of years to regenerate (Mack et. al. 2011). This layer stores vast quantities of carbon with the potential to contribute to GHG cycles, altering the carbon cycle of the entire boreal region (Lorianty et. al. 2014).

Some ecological processes support negative feedback loops to soil carbon loss and these vegetative cycles slow permafrost retreat or even contribute to permafrost level recovery (Brown et. al .2015). Mitigating influences exerted by the ecological processes of vegetative dynamics slow permafrost loss and contribute to permafrost return over time (by replenishing the insulating vegetative layer [Bret-Harte et. al. 2013]). Surface deformation caused by thermokarst may not be as detrimental to permafrost presence or longevity as some research indicates, in fact under the right conditions topographical surface alteration may be beneficial to permafrost layers (Jorgensen et. al. 2015). Jorgenson et. al. (2015) found that increased surface biomass resulting from the altered hydrology caused by thermokarst increased surface biomass thus providing insulation to permafrost that favored layer recovery.

The short-term result that Brown et. al. found (2015) is an initial increase in the volume of grasses and forbes that grow near thermokarst troughs. Temporarily increased vegetative growth can initially exert pressure on permafrost through two ways. First, warmer soil temperatures are favorable to the activity of microbial communities within thawed soil horizons. As these bacterial communities increase metabolic activity they increase the volume of available nutrients in the soil that shrubs and grasses can exploit (Routh et. al. 2014). This encourages plant growth with subsequent establishment of grasses and shrubs. As these initial exploitative species expire, they build up an insulating layer of surface detritus that decomposes to form new layers of carbon rich strata overlaying permafrost (Brown et. al. 2016). Initially this can make the area more vulnerable to surface fire pressures; however, eventually these areas become a "blanket" that preserves permafrost (Ping 2008). Second, regarding deeper permafrost layers, drainage of surface troughs increases resulting in migration of water from upper soil horizons into soil strata adjacent to permafrost (Jorgenson et. al. 2015). The saturated soils within the hydrologic column freeze more readily during the winter months and recompose a thicker active layer (Jorgenson 2015). Depending on the initial temperature of migrant water in the hydrological column, when it reaches the colder permafrost soil layers it can become impounded beginning a cycle of permafrost regeneration.

While initial thermokarst land subsidence can prove beneficial to the growth and accumulation of biomass density near term, eventually thermokarst troughs degrade and can form ponds or lakes with a different flora profile. Initially biomass composition consists of grasses and shrubs that gradually transition to aquatic mosses and grasses that contribute to the formation of stabilizing ice wedges that increase permafrost (Jorgenson; 2015) density. As the transitory process of biomass shifting progresses, water and heat flux begin to decrease and as stated previously, soil organic carbon layers begin to recover in depth. As the migratory water refreezes near the permafrost layer, this newly formed active layer becomes more stable and acts like an insulator (Bret-Harte et. al. 2013). Small vascular plants and mosses are the most beneficial to permafrost recovery as these plant species typically transition to peat layers that provide the greatest insulation for growing permafrost layers (Jones et. al. 2016; Jorgenson et. al. 2015 [Figure 3-9]). Initial SOC carbon losses are observed in collapse scar bogs (Brown; 2015); however, these areas can become carbon sinks due to short term rapid buildup of detritus despite a net loss in carbon storage. Additionally, mosses and small vascular grasses may pull carbon nutrients from the soil during metabolic processes (Routh 2014) only to return a greater quantity of carbon to these layers during peat formation (a result of plant cellular respiration). These processes can cause a noticeable fluctuation of regional soil temperatures and exert a restorative influence that appears to be stronger than the influence of warming air temperatures alone (Jorgenson; 2015), and illustrates the resilience of this system.

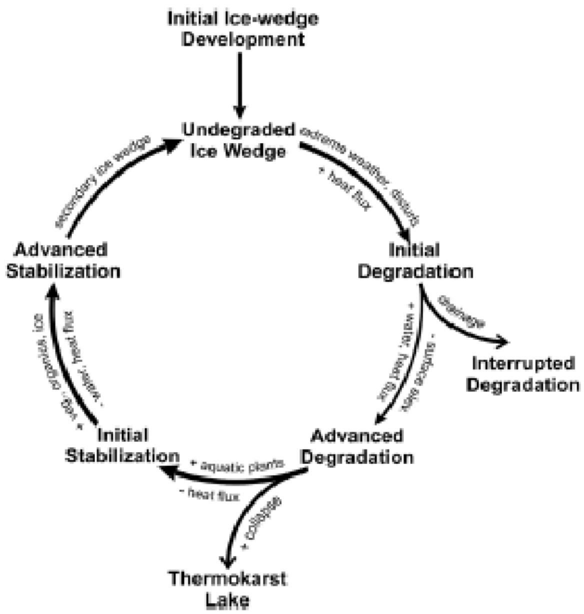


Figure 3-9: *Conceptual model of cyclic ice wedge degradation and stabilization. Main stages are shown in bold, while biophysical factors affecting transitions are shown along arrows. Positive feedbacks with increasing heat flux are on the right, while negative feedbacks with decreasing heat flux are on the left. Graphic and caption from Jorgenson et. al. 2015.*

Fire Interactions with Permafrost

From 2000 until present, larger and more frequent fires have burned in the boreal region and especially within areas where continuous and discontinuous permafrost are concentrated.

Fire severity, as defined by the amount of acreage burned (this is the current general measurement consensus, since an industry wide index of fire severity based on other factors is not widely agreed upon [Boby et. al. 2010]) is particularly concerning because since 2000 larger fires have trended toward occurring in areas overlaying the continuous and discontinuous zones. Fire encourages thermokarst in areas underlain by continuous and discontinuous permafrost (Liu et. al. 2014). In one study of tundra fires near the Anaktuvuk and Kuparuk Rivers, Liu et. al. (2014) found postfire subsidence ranging from 2 to 8 cm within fire zones and no significant subsidence ($p<0.01$) outside of study area fire perimeters. Pre-fire years showed seasonal thaw subsidence ranging from 1-4 cm which was not very different from postfire thaw subsidence where this measure (not accounting for fire induced subsidence) showed only minor active layer variation of 2±1 cm to 4±1 cm throughout the fire affected tundra range (Figure 3-10).

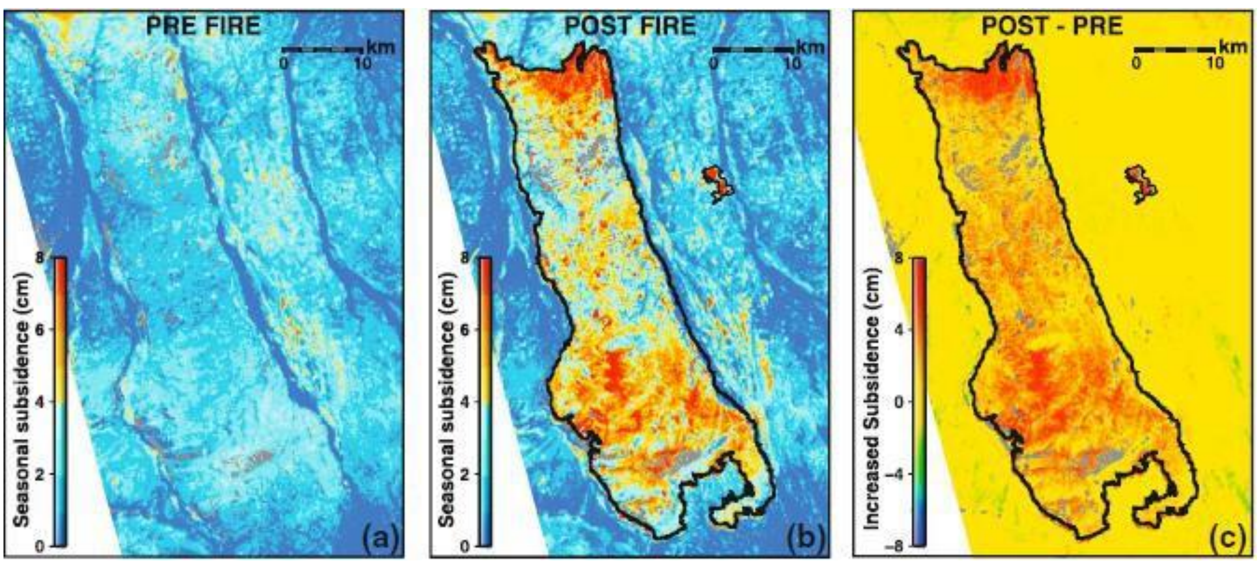


Figure 3-10: Thaw-season subsidence averaged during (a) pre-fire years and (b) postfire years, respectively. Grey areas represent unreliable subsidence measurements caused by coherence loss. (c) The difference between postfire and pre-fire subsidence, i.e., Figure b minus Figure a. Image and caption from Liu et. al. 2014.

The interrelation between soil carbon and permafrost, while intricate, is relatively straightforward. Climate influences permafrost dynamics on a regional level, and biomass accumulation and increased fire activity affects permafrost on the patch and landscape levels. Thermokarst processes are directly related to permafrost retreat and can alter both hydrology and vegetative mass/ composition, again, generally at patch and landscape scales. While climate initially decreases permafrost levels (opening stocks of carbon to be fuel sources), in time permafrost levels can recover as vegetative life cycle process replenish insulating organic layers that become sequestered when permafrost aggrades. However, regional carbon cycles are somewhat permanently affected because of the millennial time scales that these regenerative processes occur on.

3.3 Climate Change Influences on Carbon and Fire Cycles

Climate is dynamic and these changes are rarely the result of a single factor although anthropogenic influences do exert some influence. To answer how altered climate as defined warmer, longer, and potentially drier summers will alter regional carbon cycles (as influenced by permafrost and successional dynamics) and wildfires, and thus regional emissions, regional climatic data must first be examined.

Influences of Temperatures and the Pacific Decadal Oscillation (PDO) on Carbon/ Fire Cycles

Temperatures have risen in the boreal region over the last century (Wendler & Shulski 2008) and caused overall regional warming while decreasing precipitation levels in the north and increasing these levels in the southern portion. Fairbanks has experienced a 1.4° C mean temperature increase over the last 100 years, with a subsequent lengthening of the growing season by 45% (Figure 3-11 [Wendler & Shulski 2009]). Although regional warming is influenced by more intense fires with shorter return intervals (Hartman & Wendler 2005), the Pacific Decadal Oscillation (PDO) (Stavros et. al. 2014) exerts a more prominent influence on regional climate.

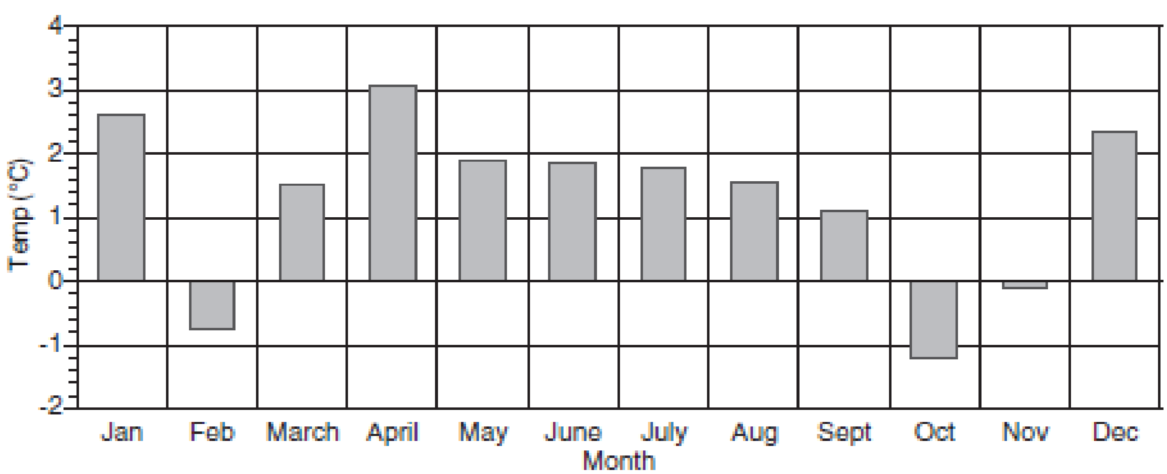


Figure 3-11: Annual mean temperature change at Fairbanks from 1906-2006 as calculated for each month (Image from Wendler & Shulski 2008).

The PDO is a shift in oceanic hydrological and air currents in the North Pacific Ocean and Bering Sea that exerts a pronounced regional climatic effect in the boreal forest region. In 1976, the Pacific Decadal Oscillation (PDO) shifted into its positive phase causing up to a 3.1° C increase in temperatures from the PDO's negative phase. The PDO index transition in to positive values corresponds with higher temperature trends throughout the region (Figure 3-12).

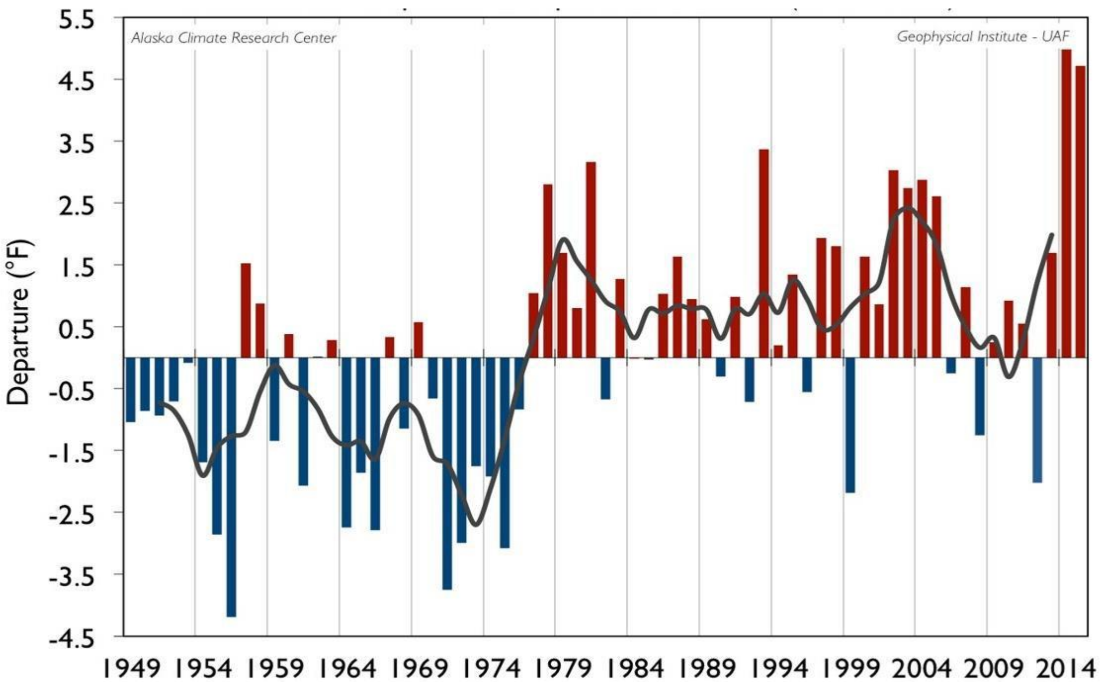


Figure 3-12: Mean temperature departures for Alaska from 1949 through 2014. Temperature shifts toward an increase in average temperatures corresponds with the 1976 Pacific Decadal Oscillation (PDO) transition toward the positive phase. Image courtesy of the Alaska Climate Research Center, and compiled from data by the UAF Geophysical Institute (2014).

Hartman & Wendler (2005) found a positive correlation between this shift into the positive phase and an increase in temperatures throughout the region; temperatures increased annually by an average 1.7% in interior Alaska and the Arctic region (that borders the boreal region to the north) experienced an average 1.9% (Table 3-2).

Table 3-2: Change in mean temperatures (°C) from 1951 to 2001 based upon linear least squares regression trend line (bold indicates significance at a probability greater than 90%; shading indicates significance at a probability greater than 99%). Graph data and caption from Hartman and Wendler 2005. Data for the rest of the state is excluded from this table since the arctic and interior data are the area of interest (Boreal ecoregion). The top row is months of the year (M-March, A-April, M-May, etc.).

	Annual	MAM	JJA	SON	DJF
Interior AK	**+1.7**	**+2.6**	**+0.8**	-0.4	**+3.7**
Arctic Region AK	**+1.9**	**+2.1**	**+1.4**	+0.7	**+2.8**

Since warm air (a result of the PDO positive shift) holds more ambient moisture than cold air mean snowfall and rain percentages increased in the interior (but decreased in the Arctic

[Wendler & Shulski 2008]). The mountainous regional topography causes moisture to be largely deposited within the southern range of the boreal interior region, ultimately resulting in drier air making its way north (Hartman & Wendler 2005). This caused a decrease of as much as 43% in late winter and early spring precipitation in the form of snowfall or rain in northern regional extents (Kasischke & Turetsky 2006; Hartman & Wendler 2005). Regionally, water vapor is also a potent GHG, trapping a great deal of radiant energy from the sun and increasing ambient temperatures. As the PDO shift brings warm dense air into the region, temperatures and precipitation should increase, most notably during the winter months when cold dry Arctic inversions trap air currents within the river valleys of the boreal region (Hartman & Wendler 2005).

Table 3-3: Percent change [defined as (1977–2001 minus 1951–75)/1951–75] in total precipitation (TP) and snowfall (SF) (bold indicates significance at a probability greater than 90%, shaded indicates significance at a probability greater than 99%) Graph data and caption from Hartman and Wendler 2005. Data for the rest of the state is excluded from this table since the arctic and interior data are germane to the area of interest (Boreal ecoregion).

	Annual %		MAM (%)		JJA (%)		SON (%)		DJF (%)	
	(TP)	(SF)	(TP)	(SF)	(TP)	(SF)	(TP)	(SF)	(TP)	(SF)
Interior AK	+7	+14	+4	-8	+7	--	+7	+**21**	+12	+**20**
Arctic Region AK	-16	-9	-**43**	-26	-1	-24	-21	+3	-**39**	-13

Shifts in temperature and precipitation are more pronounced in the interior as pressure and wind patterns tend to disperse much of their energy before arriving in these landscapes (Calef et. al. 2015; Hartman & Wendler 2005). Precipitation in southern and central interior landscapes increased while precipitation in the Arctic landscape decreased rather significantly (Table 3-3). The decrease in Arctic precipitation is significant because as this portion neighboring the boreal region to the north loses annual rain and snowfall input, it becomes drier and soils become less waterlogged, thus becoming more susceptible to fire activity that was not previously present (Bret-Harte et. al. 2013). Where prolonged periods of dry, warmer than average temperatures become prevalent in these vulnerable Arctic extents of the region, growth of large wildfires is favored (Bret-Harte 2013). Monthly climate influences on wild fire is strongly correlated to average temperature in the 1-2 weeks post fire ignition (Abatzoglou & Kolden 2011). Rain cycles defined by a shorter interval of return and higher levels of output act to naturally suppress wildfires in landscapes that are inaccessible to human fire suppression efforts (Abatzoglou & Kolden 2011). Areas in the southern portion of the boreal region should benefit from the positive shift of the PDO (through greater precipitation that reduces flammability and number of fires) while areas in the northern portion may be adversely affected over longer time periods (drier conditions that favor increased numbers of fires).

Hartman & Wendler (2005) found similar mean annual temperature departures while analyzing regional temperature variations in interior Alaska (Figure 1 in Appendix A). Although data exhibit seasonal fluctuations from year to year, the trend of the mean is toward regional increase. Excepting the 1950's, the data show the sharpest increase in mean seasonal fluctuation around the mid 1970's—in accordance with the positive shift in the PDO (Hartman & Wendler 2005). These shifts cause varied impacts to fire regimes and soil carbon stocks based on spatial distribution (B. Young et. al. 2016), however, if temperatures continue to rise, the net result will be increased biomass net primary production (NPP) with larger fuel volume (Harden et. al. 2000). Warmer temperatures and altered precipitation rates (both rain and snow fall) strongly affect carbon deposition by altering NPP (Amiro et. al. 2010), biomass composition, and soil thermal dynamics. Warmer temperatures favor increased decomposition rates altering soil chemical composition (greater quantities of nitrogen and metabolic carbon [McGuire et. al. 2009]) resulting in favorable growing conditions (Prentice & Harrison 2009). Initially warming climate is thought to cause an increase in carbon cycling (through increased decomposition [North & Hurteau 2010]), releasing more soil carbon stocks into the atmosphere because of increased fires (Flannigan et. al. 2009) and decomposition (a source of CH_4).

Climate Change Impacts on Vegetation

Increases in mean temperature and increases in precipitation patterns (in the southern extent of the region) create conditions favorable to the northward spread of black spruce and deciduous dominated forests that can change carbon cycles and fire dynamics throughout the region (Goetz et. al. 2007) altering vegetative composition and regional fire cycles. Warmer regional climatic conditions favor novel shifts in spatial distribution and connectivity (B. Young 2016). Paleo-ecological literature generally supports a potential latitudinal advance of the tree line in the face of warmer mean temperatures, ultimately leading to replacement of large areas of tundra with coniferous forest stands (Bachelet et. al. 2005). This can be problematic as these extents are not well adapted to the kinds of fires that generally burn in the southern forest regions and may result in spikes in carbon emissions from that landscape (Mack et. al. 2011).

Much of the literature concurs that ground temperatures directly influence the potential for surface vegetation (and near surface carbon stocks) to become fuel sources for novel fire regimes (Barrett et. al. 2011). The effects of ground temperature shifts are dependent on spatial relationships between low lying and mountainous areas; landscapes defined by mountainous terrain will experience less fire regime novelty (due to more steady mean temperatures) and thus less pronounced emissions. Warmer average temperatures favor more vegetation growth and an increased spatial variability of forests in the boreal region. Ground temperature data (Jafarov et. al. 2012) illustrate mean ground level temperature increases based on A1B emission scenarios (Figure 3-13). Jafarov's (2012) model predicts between a 2.4-3.7% increase in mean ground temperatures over the coming century—temperatures that will lead to more snow free days, particularly in the boreal region. When comparing these maps with the boreal ecoregion (Figure 1-1), increases in vegetation density and successional trajectories that favor increased fire risk will become more likely in the 21st century. These warmer temperatures will increase above ground fuel pools (and labile carbon stocks due to permafrost retreat) with resultant increases in regional GHG emissions.

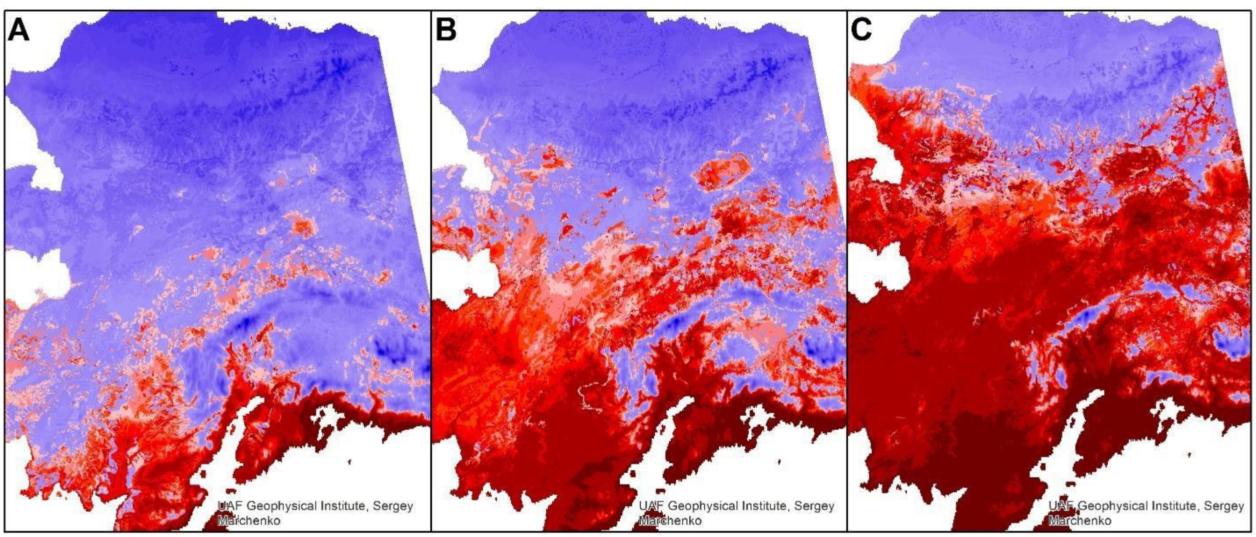


Figure 3-13: Changes in Alaska ground temperatures within the range of -15 to 10.5° C, with blue areas ranging from -15 to 0° C and pink to red areas representing a change of 0 to 10.5° C. (A) shows the average predicted change in ground temperatures in 2010. (B) is the average predicted change in ground temperatures by 2050, and (C) shows predicted change in ground temperatures by 2099. If current prediction models represent an accurate rise in ground temperatures, areas as far north as the Arctic tundra on the North Slope could be warm enough to favor considerably altered biomass composition. Maps created by the UAF Geophysical Institute, Fairbanks, AK from data found in Jafarov et. al. 2012.

Climate Change Impacts on Fire Cycles & Soil Carbon Dynamics

Climate is the primary regional influence on frequency of fire in the boreal region and related SOC loss; however, other factors influence fire spatial variability and SOC cycling on the landscape and patch scales. Altering spatial arrangements of fuels shift fire regimes and soil carbon cycles with concomitant patch and landscape influences on climate. Timing of fire ignitions is critical—fires that begin early in the summer have a greater chance of either being extinguished by late spring rainstorms or remaining small scale due to unfavorable ground conditions (saturation with snow melt that keeps ground level flora damp); or they may become large fires if an early spring marked by lower than average precipitation occurs (Hardin et. al. 2000). These types of fires can also be suppressed more readily (given their proximity to human settlements) provided access is not an issue.

Conversely, fires that start in the later summer months can quickly become large and severe since drier summers favor large fires (Flannigan 2009), and severity can increase dramatically since forest stands that are most prone to combustion (primarily black spruce dominated stands) have dried out sufficiently to make them ideal fuel pools (Lloyd et. al. 2005). If large fires are ignited in later summer months (the primary ignition sources of these fires are lightning strikes from late summer storms) they have the potential to become holdover fires (Alaska Interagency Wildland Fire Management Plan 2016) and produce more GHG emissions than surface fires alone. Late season fires can increase surface erosion if fires burn past periods of increased spring and early summer rainfall that promotes floral growth (Keeley 2009). As surface carbon stocks decrease and mineral soils become exposed, successional changes that favor deciduous species occur (Bond-Lamberty et. al. 2007) and phenological changes occur that favor more rapid replacement of these deciduous forest stands (Yiqi Luo 2007; Root et. al. 2003).

Post fire carbon layer recovery is largely driven by intensity, and severity of fire as well (Keeley 2009). The literature broadly establishes that more intense fires (defined by greater than normal combustive energy outputs) cause higher rates of tree mortality (severity). The increased quantities of combusted biomass can account for 4-6% of annual carbon emissions during active fire years (Hurteau & Brooks 2011). Plants are sensitive to CO_2 concentrations in the 200-300 ppm range (Prentice & Harrison 2009) and when atmospheric concentrations of CO_2 increase by 200 ppm NPP increases on the order of 23±2% (2009). The increased CO_2 concentrations may increase NPP despite soil nutrient limitation (specifically N_2) that demonstrably limits regional biomass growth (Prentice & Harrison 2009). Although sensitive to atmospheric CO_2 concentrations, plant photosynthesis and metabolic activity is a strong sequestering influence on atmospheric carbon. This metabolic activity may offset initial carbon pulses (Hurteau & Brooks 2011) with a neutral net effect to climate considering energy transfers with respect to carbon outputs (Randerson; 2006).

Fire's Influence on Climate

Fire cycles are predominantly influenced by climatic factors; however, fire asserts influence on regional climate warming through two main pathways: first the increased levels of atmospheric CO_2 due to above ground biomass and SOC combustion, and second, through the output of large quantities of fine carbonaceous particulate matter that increases surface and near surface atmospheric albedo. When fires occur more frequently in this region following increases in biomass density, a greater portion of fine particulates are released into the upper atmosphere contributing to a reduction in surface temperatures and cloud cover suppression (which can lead to localized weather anomalies such as droughts [Liu et. al. 2014]). Damoah et. al. (2006) used FLEXPART modeling (from satellite imagery and data) to show that fire can propel combusted particulates deep into upper levels of the atmosphere through pyro-convection. This results in a shading effect from particulates and concentrations of combustion gasses causing cool spots in stratospheric layers (Damoah 2006). The heat from large fires causes water vapor in the soil to be propelled up toward these "cool spots" with subsequent condensation and cloud formation. The clouds cause moderate shading that temporarily lowers surface temperatures in the period immediately following fire extinguishment (Damoah et. al. 2006). Airborne microscopic black carbon particles absorb considerable quantities of solar radiation, again causing a localized cooling effect immediately following fire (Liu et. al 2014; Ding et. al. 2012).

Warmer climate fueled frequent fires have burned significant quantities of soil bound carbon—Ding (2012) found that fires spurred on by warmer mean temperatures released up to 6 TgC over a period from 1960-2006. Had warming not induced greater fire activity, 125 TgC would have been stored in the Yukon River Basin (which transects the northern central edge of the boreal region) instead for 119 TgC (Ding et. al. 2012). This loss of carbon from the soil ends up in the polar region atmosphere where concentrations of GHG's and related warming effects can occur twice as fast as in lower latitudes (B. Young et. al. 2016). A. Young et. al. (2016) found a correlation between mean temperature and precipitation as driving factors of fire and thus soil carbon loss projected into the 21st century. When large quantities of CO_2 are input into the atmosphere due to increased regional fire activity, a positive feedback loop between warmer temperatures (that directly contribute to fire activity) and shorter fire return intervals is created that becomes self-sustaining once climatic thresholds are crossed.

When current regimes were compared with paleo-records of fires (extrapolated from analysis of charcoal layers in soil horizons) patterns showed that current warming is driving more frequent and severe fires (Kelly et. al. 2013). The frequency of return and the intensity of burning has surpassed the fire regime limits of the previous 10,000 years (Kelly; 2013). Fire regimes as a variable are dependent on climatic conditions—climate change causes warmer and longer summers, with increased flammability in fuel pools. At a regional scale, higher summer temperatures support novel landscape connectivity (B. Young et. al. 2016) regardless of fuel type. Warmer temperatures cause changes in ecological processes that can both offset fire effects and support increased fire activity. The result is a novel fire regimen (when compared with previous millennia) defined by more intense and severe fires at broader regional scales. Although there is much spatial variability due to topography and other natural barriers (rivers, lakes, and streams) the literature indicates an overall increase in areas burned although some smaller landscape patches showed decreases in burning or no change at all (Flannigan; 2009). There is a complex interrelationship between fire and climate (Figure 3-14), that is complicated by the addition of the factor of the terrestrial influences of permafrost dynamics; however, on a regional scale climate exerts the dominant influence on fire cycles.

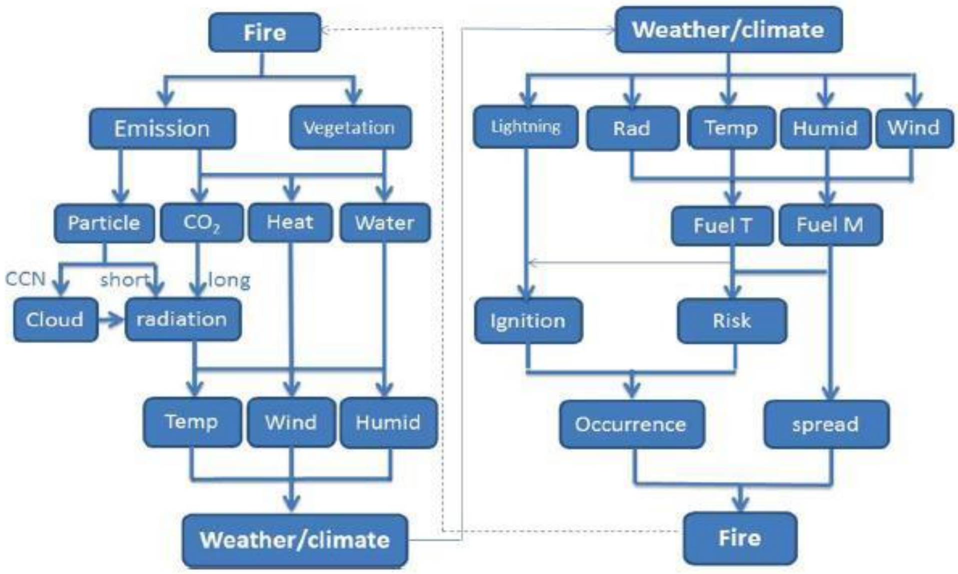


Figure 3-14: Diagram of physical processes for fire's impacts on weather and climate and feedbacks. Diagram image and caption from Liu et. al. 2014. Fire is primarily influenced by climate, fuel temperature and moisture, and fuel load. Fire however can exert influence on climate as increased particulates and CO_2 contribute to warming that supports a positive feedback loop between fire activity and climate.

3.4 Role of Wildfire and Forest Succession

Soil carbon and related emissions cycles are complicated by complex fire and forest succession dynamics that occur at all ecosystem levels (patch, landscape, and region) within the study area. The literature generally agrees that black spruce dominated forest stands are the most susceptible to large stand replacing wildfires, and are the greatest source of carbon emissions during unprecedented fire events (Allen et. al. 2010; Miquelajauregui et. al. 2016; Wang & Kemball 2010). Novel fire regimes affect fire (and associated carbon cycles) by fostering increased connectivity of dry surface fuel stocks or large pools of combustible soil carbon in near surface horizons (Stavros et. al. 2014). Increases in summer temperature ranging from 0.73-1.19° C from 2010-2039, and 2.33-3.08° C from 2070-2099, coupled with increasing spatial variability of precipitation will lead to shorter fire return intervals on the regional scale (A. Young et. al. 2016). Fire perimeters are susceptible to warmer temperatures and altered weather conditions in the days and weeks following ignition (Abatzoglou & Holden 2011) and can spread more aggressively if favorable temperature and wind conditions are prevalent. Unprecedented fire activity of previous decades (Kelly et. al. 2013) will drive novel forest structure, connectivity, and ecosystem services into the 21st century (Johnstone et. al. 2009 Young, B. et. al. 2016).

Alaska Fire Service Data when analyzed with other datasets (Sections 2.1.1-2.1.3) support literature syntheses in answering perhaps the most complex question regarding how successionary shifts and associated ecological factors increase or decrease novelty in regional fire regimes, restore permafrost layers, and limit fire induced carbon emissions.

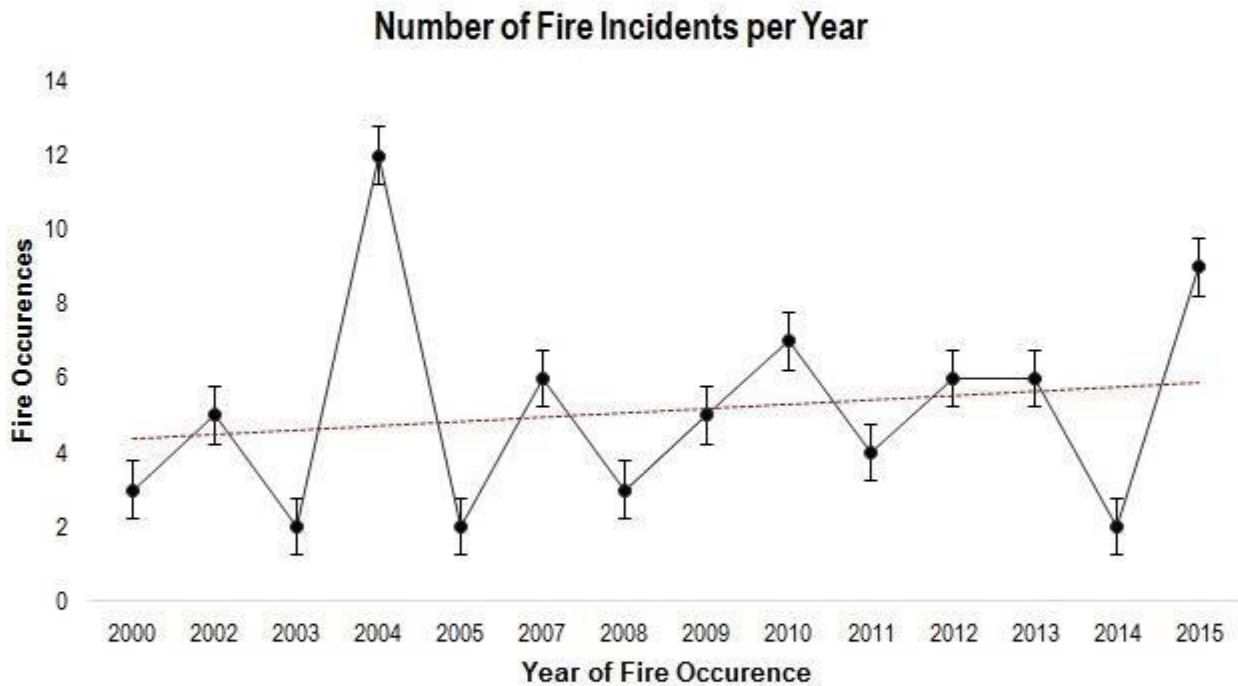


Figure 3-15: Regional fire activity from 2000-2015 (excepting 2001, 2006). The number of fires occurring in the region shows a slight increase over the 15-year period, and is directly influenced by increases in average summer temperatures. Data from the Alaska Fire Service and Alaska Geophysical Institute- UAF, processed with ArcGIS® software.

Regional fire activity has somewhat increased in the period from 2000-2015 (Figure 3-15) and is correlated with increased average summer temperatures. Regression analyses of temperatures averaged from monthly mean temperatures for June, July and August of each year (2000-2015), was conducted with fire occurrence (the count of shapefiles per year) and showed correlation between temperature increases and fire occurrence (r^2= 0.324, p=0.03). This indicates that fire occurrence can be attributable to temperature increase. Fire size (by acreage burned) is also influenced by increasing temperatures but more strongly influenced by other environmental variables (Moritz et. al. 2012; Kelly et. al. 2013). Despite a trend in the data toward increased burned acreage from 2000-2015 (Figure 3-16), average summer temperature increases did not statistically influence the size of fires (r^2= 0.24, p=0.09). This supports the hypothesis that while increased temperatures directly influence the number of regional fires, the size of these fires and their subsequent emissions are influenced by a multitude of variables such as vegetation, topography, fuel composition and connectivity, and time of occurrence (Calef et.

al. 2015; Kelly et. al. 2013), with annual temperatures contributing only a partial influence. It is reasonable to conclude that emissions from fires cannot be predicted by temperature increase alone; emissions may decrease if fires occur in areas of sparse vegetation or carbon poor soils (Jain et. al. 2012), while they may spike (even though it is a smaller fire by acreage) if they occur in areas of dense vegetation and carbon rich soils (North & Hurteau 2011).

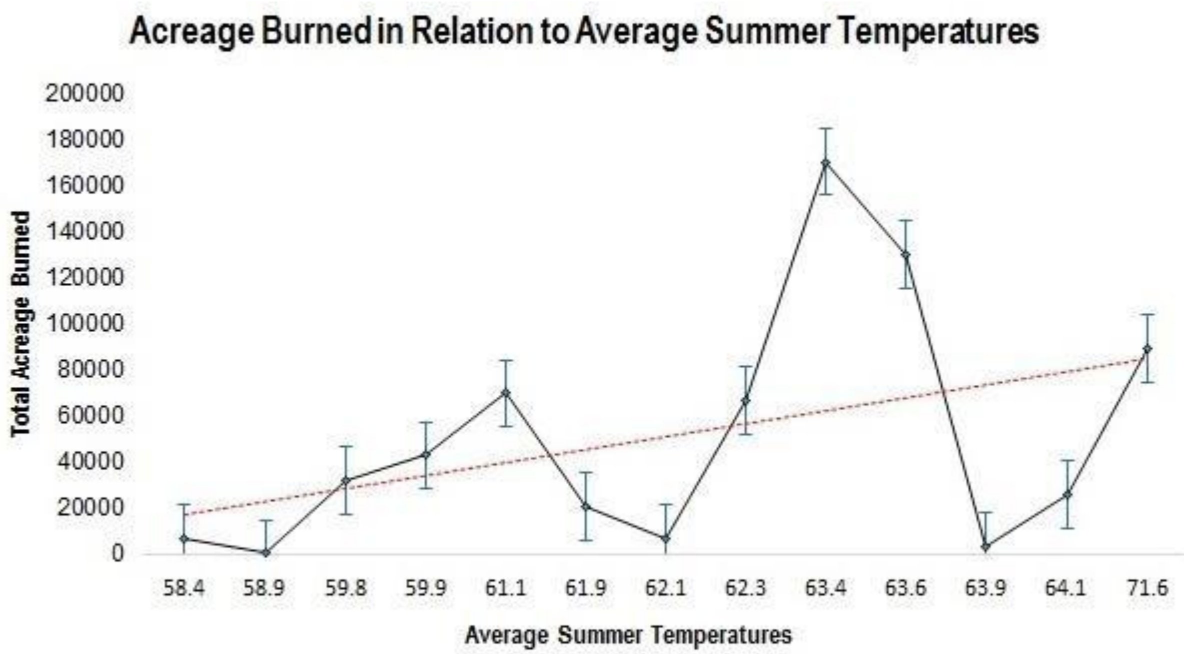


Figure 3-16: Fire acres burned from 2000-2015. The area burned is highly variable and is not the result climatic factors alone, although climate influences variables such as vegetation, soil dryness, and other important factors that influence fire occurrence and size. From analyses of data from the Alaska Fire Service, and temperature data from the Alaska Geophysical Institute at the University of Alaska Fairbanks, it is highly likely that a multitude of factors work in concert, and no one factor is responsible for fire size, or resultant emissions. Data from Alaska Fire Service and UAF Geophysical Institute, processed with ArcGIS® software.

Measures of fire severity and intensity (as touched on briefly in Section 3.3) are not uniformly agreed upon by researchers (Keeley 2009). Keeley (2009) postulated that intensity is a measure of the energy released by the various phases of the combustion process itself and no one single metric captures all relevant aspects of this energy (2009). Severity can be measured by the amount of mortality in aboveground live biomass (Keeley 2009) and in the level of biogeochemical and physical changes that take place in the upper layers of surface soil—most notably those horizons with the greatest carbon content (Boby et. al. 2010). In another example, fire severity assessment was modeled by Escuin and fellow researchers (2007) using NBR (Normalized Burn Ratio) and NDVI (Normalized Difference Vegetation Index) to show calculated indices of burn severity (as defined by changes in vegetation and surface soil profiles) within an 86.42% (±4.31%) rate of accuracy, thus illustrating the usefulness of such modeling in extrapolation applications to other fires in similar ecoregions around the globe (Escuin et. al. 2007). For this paper fire severity is generally defined as the size of fire perimeters outlined by the Alaska Fire Service (although literature considerations are factored into this definition). Severity is tied to forest recovery and invasive species exploitation (Keeley 2009) and fires marked by large amounts of post-fire tree kill with more exploitable niches for invasive species are generally agreed to be severe fires (Flannigan et. al. 2009; Keeley 2009). Severe fires have the potential to push landscapes into a mosaic of coniferous and deciduous species as late season burning increases the amount of lower flammability deciduous cover in boreal regions in central Alaska (Kelly et. al. 2013). The processes of succession as an ecosystem response are strongly influenced by the energy released by the fire disturbance (Beck et. al. 2011), and can have broad impacts to both the ecosystem and human populations (Figure 3-17).

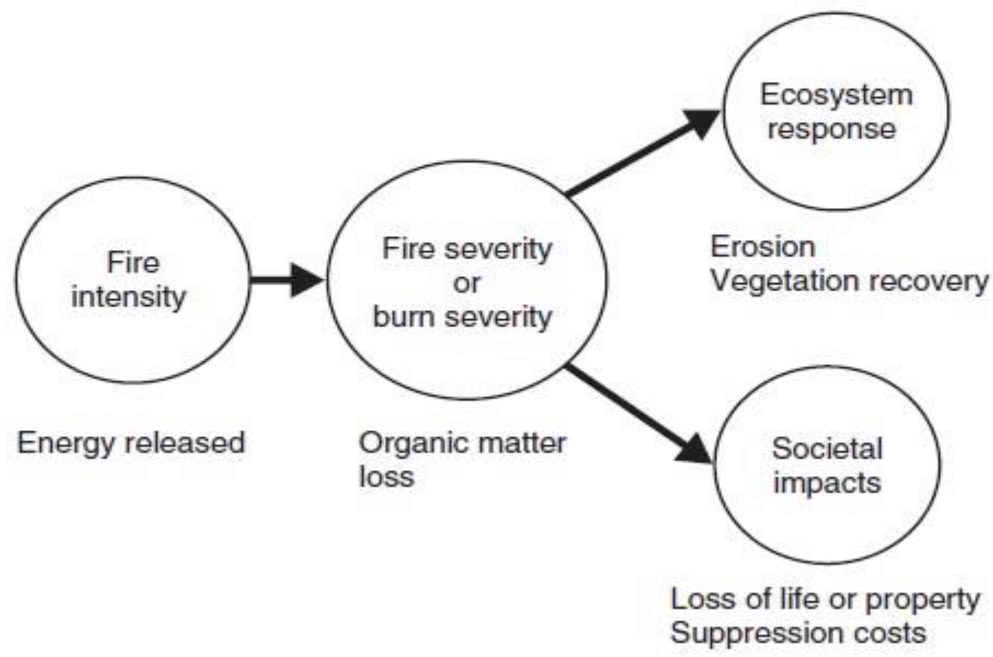


Figure 3-17: Schematic representation relating the energy output from a fire (fire intensity), the impact as measured by organic matter loss (fire or burn severity), and ecosystem responses and societal impacts. Image and caption from Keeley 2009.

Climatic influences of decreased rainfall during summer months in northern boreal extents (Brown et. al. 2016) contributes to stocks of unusually dry surface biomass that is more vulnerable to ignition from lightning strikes during frequent thunderstorms during late spring and early summer (Jiang et. al. 2015). Warmer ambient summer conditions are lengthening the summer and reduced mean soil moisture (in northern landscapes of the boreal region [Flannigan et. al. 2009]) resulting in drier vegetation and a greater risk of large, intense wildfires with shorter return intervals (North & Hurteau 2010). During years where heavy snowfall has occurred, and spring rainfall levels are above average, soil carbon layers are protected from fire damage because the increased moisture results in saturation of upper soil layers, and dense biomass secures soil integrity by its interlocking and dense root systems (Norris et. al. 2010). Under these conditions SOC and biomass loss can be minimized since wet vegetation does not generally burn, and tree mortality is reduced. Damp soils with dense biomass also reduce the fire return interval (Jain et. al. 2012), and as previously stated, low to moderate intensity fires with longer return intervals favor nutrient loading in the soil that supports sustained forest health (Ding et. al. 2015). This increase in biomass stabilizes the regional carbon cycle until the fuel load gets sufficiently large to be at risk to wide scale loss by large fires.

Post-Fire Successional Dynamics

The occurrence of more severe wildfires that remove surficial carbon pools will most likely result in the establishment and dominance of large patches of deciduous dominated forests (Pieters et. al. 2011). As briefly discussed in previous sections, intense fires remove the surface carbon layers exposing mineral soils (Shenoy et. al. 2011) that favor deciduous forests. When these types forests tend to predominate the flammability profile of the affected forest patch or landscape trends toward a lower fire risk because of the lower flammability index of deciduous dominated forests (Field et. al. 2007). Warmer, drier summers on average produce more frequent and extensive fires that can reduce the connectivity and extent of late successional refugia (McKenzie et. al. 2004) and favor altered successional trajectories and connectivity (2004). Given that Alaska is currently warming at nearly twice that of the lower 48 (Calef et. al. 2015; Young, A. et. al. 2016), similar effects could be expected to be even more pronounced in the boreal regions of Alaska with old growth forest being nearly completely replaced by younger early successional forests defined by mixed stand composition and novel connectivity (Johnson et. al. 2001).

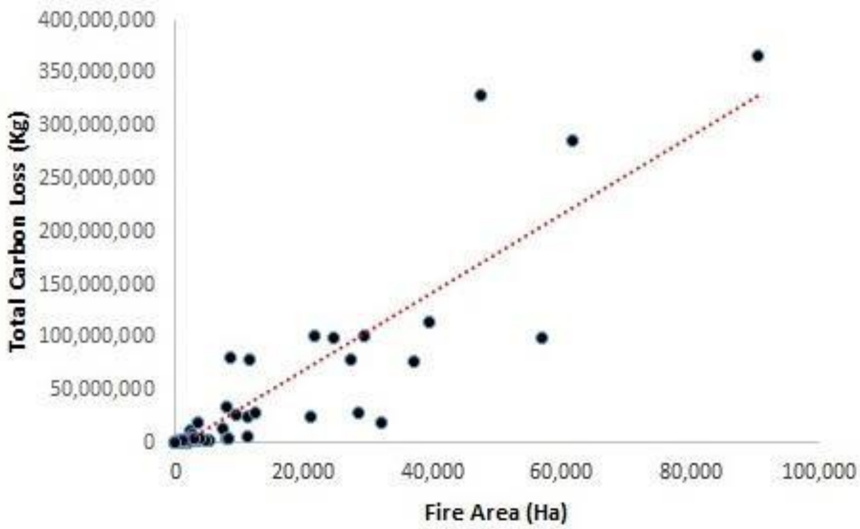
Fire activity as it pertains to ecosystem dynamics is strongly influenced by four central factors; fuels, climate and weather (as previously discussed), ignition agents, and human influences (Flannigan et. al. 2009). Another deciding factor in post-fire successional pathways is soil organic layer thickness. Post-fire establishment of dominant forest stand composition is most strongly influenced by precipitation and fire severity (Johnstone et. al. 2009). Forest composition antecedent to fire influences post-fire recovery; Johnstone and fellow researchers (2009) found a positive correlation (ρ=0.39, P<0.001, n=89) between post-fire spruce density and pre-fire density that was influenced by the level of spruce mortality (fire severity); where there was higher spruce mortality spruce recovery tended to be slow (Johnstone 2009). Fire severity accounts for over 50% of the relative influence on deciduous seedling post-fire recruitment (Johnstone: 2009) while elevation had a moderate effect; latitude, moisture, and proximity to the nearest unburned stand of deciduous or mixed deciduous stands exerted little to no influence (2009). Johnstone (2009) also found a correlation between densities of spruce and deciduous seedlings (ρ= 0.43, P<0.001); the range of relative dominance of spruce versus deciduous seedlings was widely varied in post-fire sites. Area burned exerts influence on successional pathways as Barret et. al. found that fires that burned in the boreal region in 2004 were the largest since the mid-1950's and this influenced composition cover changes (Barrett et. al. 2011).

Barrett (2011) and researchers also found that in areas with an organic layer <3 cm in depth (which accounted for 14% of their study area in Alaska's boreal region or 1520 km^2 burned in 2004) had a strong probability of converting from coniferous dominated (primarily black spruce) forest stands to deciduous forest stands. Based on their model results (Barrett; 2011) areas dominated by deciduous growth potentially can increase from 10.5% to 11.2%, and increase codominant conifer and deciduous forest stands from 9.8% to 11.1%. These potential changes can affect as much as 2% of the Alaskan boreal region and 4.2% of black spruce dominated regional areas. Given these modelled trends, and the fact that fires remove soil carbon layers exposing mineral soils (Pieters et. al. 2011) thus strongly favoring deciduous recruitment, the boreal region may become a mixed codominant landscape within ~200 years (Barrett; 2011).

Pieters (2011) also found that in areas of high severity burning had higher fractions of post-fire deciduous vegetation in the 10 years following severe fires that occurred in 2001 or later (mean DF= 75%, n=81, P<0.001). Higher severity burns also show greater levels of aboveground biomass (P= 0.039) than lower severity burns after a period of 30+ years post severe fire event. A small fraction of the organic layer consumed was related to tree stand density (R^2= 0.16, P<0.05) and ordination of post-fire data showed that deciduous tree abundance increased with increases in the amount of consumption of the organic layer (Gibson et. al. 2016). While fire did not affect environmental variables at a statistically significant level, environmental variables did effect tree abundance (R^2= 0.43, P<0.001) with elevation exerting the greatest influence. Gibson's study (2016) shows that fire severity, and certain environmental conditions not directly influenced by fire directly influence deciduous recruitment (Gibson; 2016). Following fire, even on patch scales of a landscape, the initial successional trajectory favors deciduous plants (Johnstone et. al. 2009) that stabilize surface carbon soil layers (and ultimately reduce the risk of future forest fires). Deciduous species replenish surface carbon layers by shedding leaves that build up the surface detritus layer covering mineral soils (Soja et. al. 2006). Topography, temperature, SOC mass, and organic layer (OL) depth all affect selection of deciduous species post fire. Lower elevations, higher mean summer temperatures, shallower OL depths with lower concentrations of organic matter, all favor deciduous recruitment post-fire. Dash and fellow researchers (2016) found that land cover influences also strongly effect areas burned as percentage of areas burned correlated positively with the percent cover of coniferous forest (ρ= 0.25, P<0.001). Prevailing cooler and wetter conditions post fire favor the establishment of coniferous forests per paleorecords of central Alaska (Hu et. al. 2006). As temperatures warm, and fires burn with greater levels of severity, deciduous species are favored in successional processes (Calef et. al .2015).

Fire Effects on Soil Carbon

Analysis of SOC data taken from the NCSCD (Hugelius et. al. 2013) and fire perimeters from the Alaska Fire Service (afs.ak.blm.gov) shows corollary relationships between the amount of soil carbon lost and acreage burned. Larger areas lost more SOC mass during their fire seasons (r^2= 0.79, P< 0.05) indicating a positive relationship between carbon loss and area (Figure 3-18); however, this relationship does not account for pre-fire forest composition or topography, and soil carbon loss may not be a linear relationship when these variables are considered. As fires on the landscape and regional scale burn larger areas, carbon emissions may drastically increase in the future, and be exacerbated by different vegetative composition than what was extant in previous decades or centuries.



.

Figure 3-18: Correlation between the amount of SOC lost to combustion in MgC versus the calculated area of fire polygons in hectares for the period of 2000-2015. This graph shows a strong positive correlation between SOC loss and area, however, it does not account for contributing environmental factors such as warmer temperatures and the time of year for fire occurrence. Data from Alaska Fire Service data for historical fires

When large quantities of soil carbon are lost due to large fire events these areas favor the succession of deciduous tree species as large swaths of mineral soils tend to be exposed post-severe fire (Shenoy 2011). Since the largest majority of SOC is lost during July, it is likely that forest composition will emerge as deciduous or deciduous and coniferous codominant during the following spring. Examining fire data from 2000- 2015 areas burned showed a relationship between months of the year and total SOC loss due to fires (Figure 3-19), regression analysis confirms this relationship between SOC loss and month ($p<0.05$ [$p=0.016$]), indicating that the time of the year is as important to SOC loss as spatial variability in SOC pool locations or other factors (mostly climatic). The area burned was correlated to month of fire ignition ($r^2 = 0.310$, $p<0.05$) indicating that over the past 15 years of fire data there is a relationship between the month of fire ignition and the amount of area fire consumes (Figure 3-20). When fires begin later in the season, they tend to be larger, and more difficult to contain (where suppression is practical), and it is reasonable to conclude that carbon loss will increase in later months and high levels of loss will contribute to significant increases in carbon emissions into the late summer and early fall. These carbon losses may feedback into not only novel successional trajectories, but permafrost dynamics as well (loss of the insulating carbon layers may negatively affect permafrost later in the season, and for longer periods than just summer months).

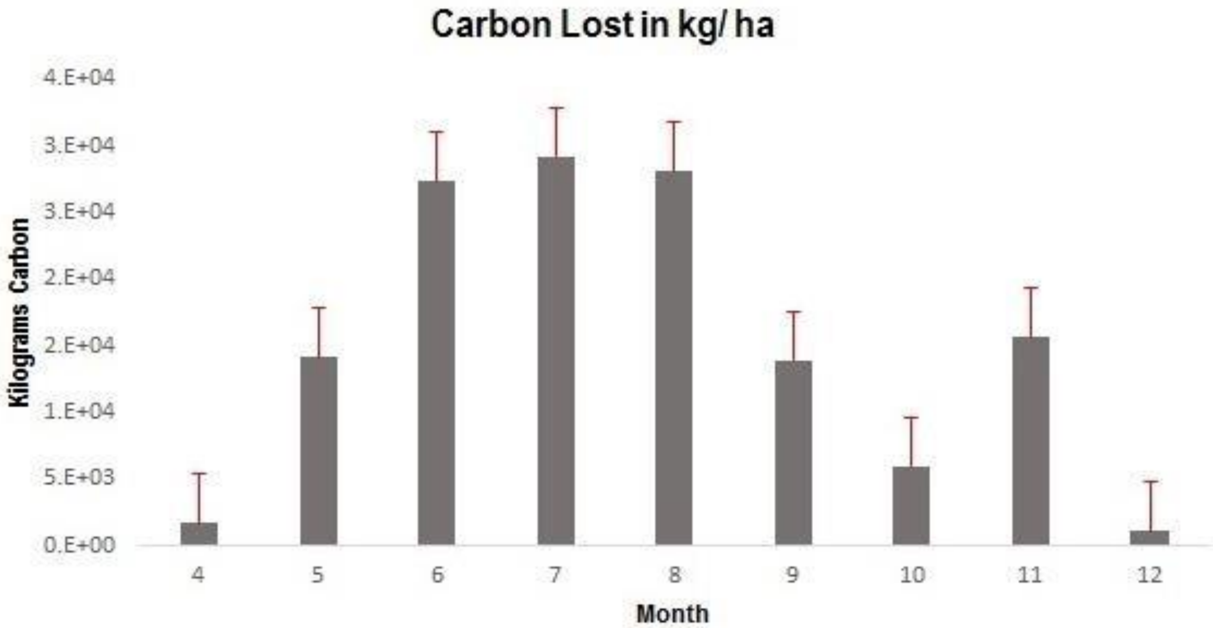


Figure 3-19: Total SOC loss by month of the year for fires from 2000-2015. Simple correlation shows an increase in SOC loss during the months of June through August, however regression analysis fails to establish a causal relationship between month and SOC loss, which is more likely associated with warmer temperatures, crier conditions, and increases in fire intensity. Data from the Alaska Fire Service.

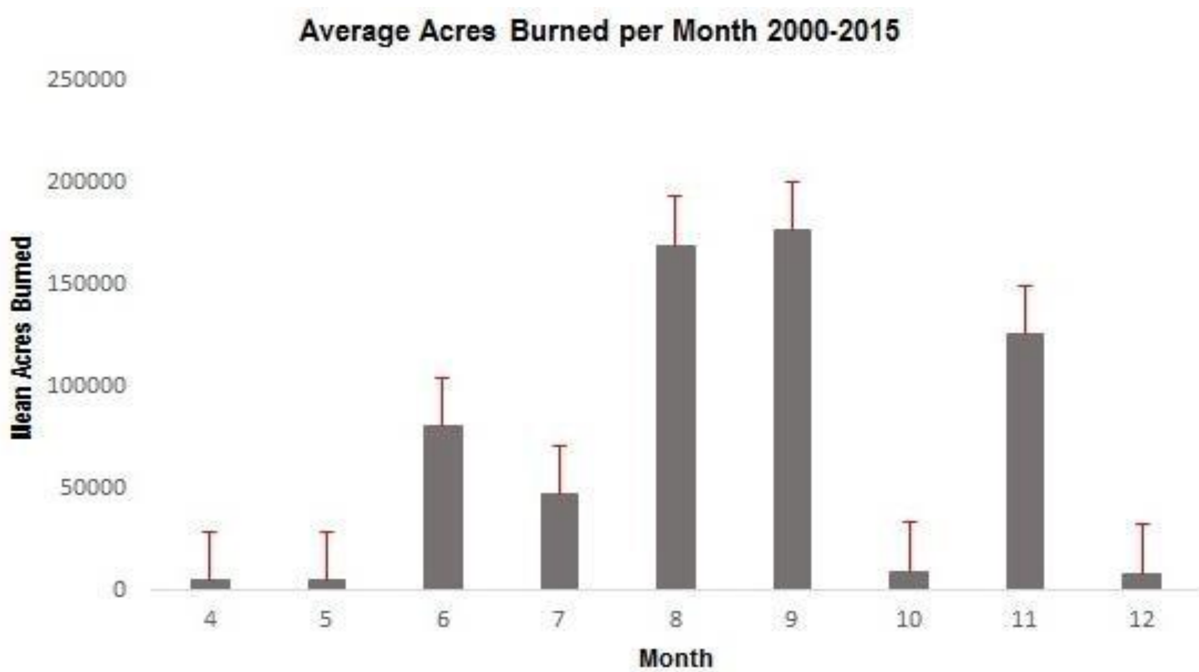


Figure 3-20: Area burned in hectares versus month of the year for 2000-2015. Data indicate that the greatest level of burn area occurs in August and September indicating the relationship between warmer, longer summers and increased fire activity that prolongs into the fall months. Fires in November are likely holdover fires since winter usually begins around the middle to end of October in the boreal region. Data from the Alaska Fire Service.

Fires recorded in November and December are likely "holdover" fire (Alaska Interagency Fire Management Plan 2016) that smolder in SOC layers until conditions are favorable the following spring for reignition (losses of soil carbon by fire perimeter and in each permafrost extent classification can be found in Table 2 of Appendix A).

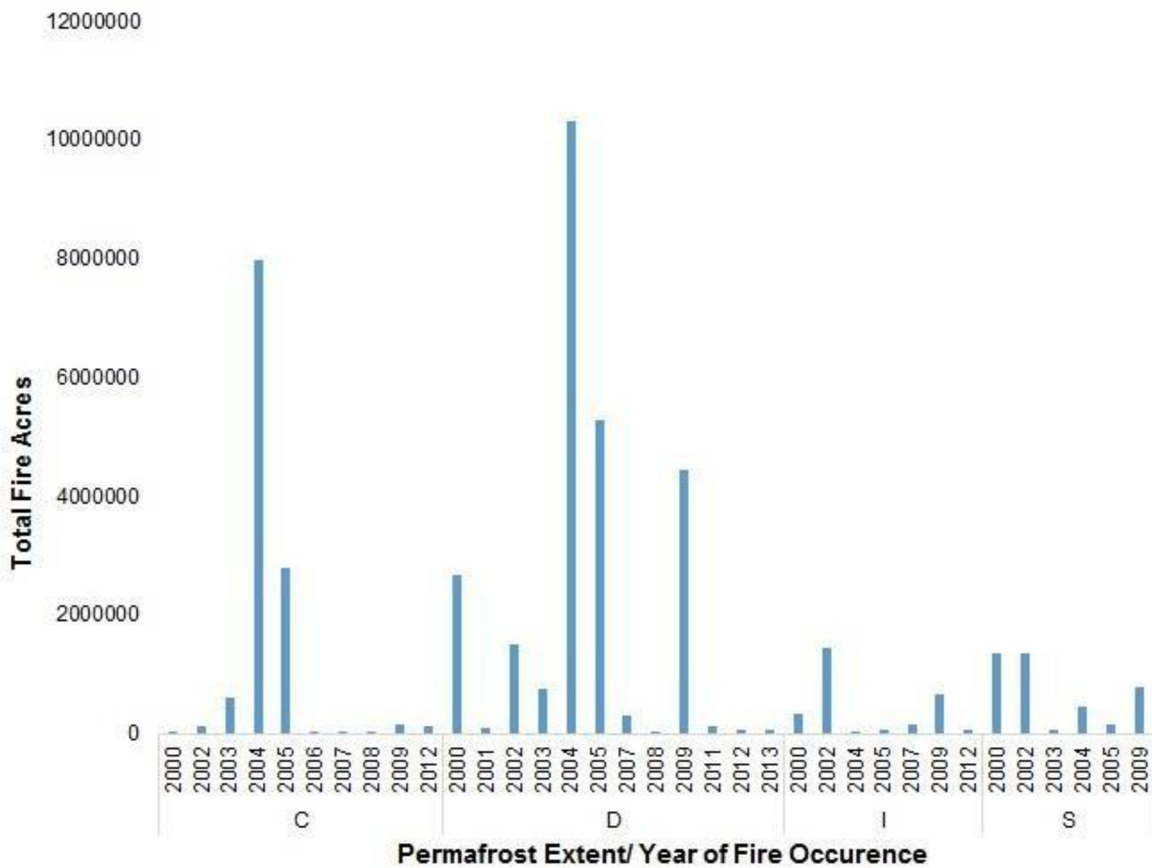


Figure 3-21: Acreage burned in hectares in each permafrost extent from 2000- Present (for which data was both present and applicable to the boreal region). Data from the Alaska Fire Service, Olefeldt et. al. 2016, and Jorgensen et. al. 2008.

The reviewed literature indicates fires in areas with high soil organic carbon concentrations have a much greater potential to contribute to a positive carbon cycle/ climate feedback loop and the period between 2000- 2015, a total of over 44,000,000 acres burned, over 25,000,000 acres within discontinuous permafrost regions (from Jorgensen 2008, ArcGIS® analyses). Permafrost extent appears to have minimal effect on wildfire size—large fires occurred in 2000, 2004, and 2009 in all permafrost extents, with some permafrost extents having more fire activity by year than others (Figure 3-21). The data analyzed through ArcGIS® support the hypothesis that climate influences fire on regional scales and carbon (from soil and vegetative sources) affects fires on a patch and landscape scale. The fire seasons in 2000, 2004, and 2009, were defined by very active fire seasons in terms of average acreage burned (Alaska Fire Service Data), a trend that if continued could cause a perceptible change to permafrost related carbon emissions in decades to come. Affects to fire from permafrost are minimal except where retreating permafrost thaws out large pools of frozen carbon increasing the fuel load for ground level fires.

Soil Carbon Effects on Succession

Thick organic layers favor the recruitment of black spruce stands in the short term following large, severe fires. In studying the persistent effects of fire severity on post-fire early successional forests, Shenoy et. al. (2010) found that spruce stands accounted for 50% of the above ground biomass in thick soil carbon layers (Shenoy 2010). However, stands with depleted organic mass had up to 90% deciduous composition (Shenoy; 2010). Sites with <4 cm OL depth showed little significant change in the proportional contribution of aspen to total stand biomass (t= 2.31, p= 0.06 [2010]). When OL depth was >4 cm aspen contribution decreased significantly with respect to total stand biomass (t= 3.58, p= 0.016 [2010]). The amount of black spruce in these areas positively correlated with OL depth (partial r= 0.65, p=0.015) and areas where the OL remained relatively intact saw a favoring of black spruce dominance in tree composition (Shenoy; 2010). When large areas of tundra are burned by fires in neighboring boreal forests, niches are opened that allow black spruce to exploit a rich extant organic layer and migrate northward, supported by warmer mean temperatures (Bachelet et. al. 2005). Bachelet's models (2005) project as much as 75-90% forest advance in the future, with this area most likely becoming boreal landscape (Bachelet; 2005).

Black spruce recruitment is generally clonal with low viability; fire return intervals of <350 years can destabilize regional populations and distribution of black spruce stands (Lloyd et. al. 2005). Counterintuitively, fire stimulates black spruce recruitment, but only fires of low intensity and long return interval (Lloyd et. al. 2005). In burned conditions black spruce reproduces effectively but this will be inhibited if fires are too intense (loss of SOC layer depth) or too frequent (less than 300-350 years return interval for large fires). This population's long term stability represents a delicate balance between fire and climatic conditions that act in concert to control reproductive output and the stability of young black spruce dominated stands (Lloyd, 2005; Bond-Lamberty et. al. 2007). Black spruce forests are well adapted to fire, but changes in the fire return interval can cause significant ecological changes to black spruce dominated stands (Kasischke et. al. 2010). Carbon stocks influence successional trajectory by their patch and landscape level responses to fire. Where highly intense fires burn, soil carbon levels are reduced, exposing mineral soils and favoring deciduous successional trajectories (Shenoy et. al. 2011). When fire return intervals are sufficiently short, a more permanent deciduous forest stand composition prevails (Euskirchen et. al. 2009). However, when fires are of moderate intensity, coniferous recruitment is favored with the native (black spruce) forest stands recurring post-fire.

3.5 Human Influences

Human interactions influence the wildfire regime in the boreal region either through activities that start fires deliberately (as in controlled burns that get out of control), through suppression activities that alter fuel loads (Calef et. al. 2008), or settlement of fire prone regions that creates unnatural landscape connectivity or corridors through which fires can spread (Natcher et. al. 2007). In general, increases in human populations result in either greater suppression activities of fire, or changes in forest composition (and connectivity) both of which act in concert to increase fire severity or activity on the landscape scale (Calef et. al. 2015). The literature reviewed for this evidentiary analysis and GIS data used focused on management zones close to human population centers, as these zones have the potential to cause the most pronounced effects to human settlements. The final key consideration of this paper is how do human land use practices influence fire cycles on the patch, landscape, and regional scale, and do these human uses increase, decrease, or cause neutral carbon emissions in areas of direct human influence.

Designated Fire Management Zones

In 1986 Alaska defined four fire management zones (FMZ- critical, full, modified, limited) to categorize fire management efforts (Calef 2008). Areas classified for full suppression showed a 10.4% ($p<0.05$) increase in area burned from 1988 until 2012 (Calef 2008). Suppression in critical areas showed increases in area burned up to 23.8 % ($p<0.01$). Fairbanks showed the only statistically significant result of analysis at a sub-regional scale with 12.4% increase in area burned ($p<0.05$) when the outlier of the 1989 fire season was excluded from the 1989-2012 datasets (Calef; 2015). Structural changes occur when human suppression activities lengthen fire return intervals and vegetative composition (Johnson; 2001). Longer return interval favor reemergence of spruce dominated forest stands (Shenoy et. al. 2011) that have higher flammability indices than mixed codominant or deciduous stands (Goetz et. al. 2007). Increased development of intermediate height fuels that increase connectivity between surface and canopy/ crown fuels makes forest stands more susceptible to more severe fires as ground level fires become high mortality rate canopy fires under extreme weather events and where humans start fires in the region (Johnson; 2011). This indicates that areas of greatest suppression ultimately are at a much higher risk of large fires due to mixed forest stands of moderate flammability transitioning to spruce dominated stands, and buildup of fuel loads, particularly around areas of high population density (Fairbanks, Delta Junction, etc. [Calef et. al. 2015]). Increased permissiveness (from the State of Alaska Forestry Service) in timber extraction and removal of surface fuels (dead and down) is likely to decrease the fire risk around population areas, and can stabilize patch and landscape fire cycles.

Human Ignitions from Land Use

From 1988-2005 Human fire ignitions exceeded lightning strike ignitions by nearly 50% (Calef et. al. 2008) within 10 km of populated areas, and human caused ignitions are highest within 1 km of rivers (Gaglioti 2016). Area burned also increased the closer to human settlements fires started. Within 5 km of highways an increase of 10% of area burned occurred and increases of 12% occurred within 20-30 km of highways (Calef; 2008). At 40-50 km away from highways the area burned decreased to around 7% indicating that human activity influences fires within approximately 30 km of major travel corridors (Calef; 2008). Post-industrial human activities have decreased fire return intervals in the boreal region, particularly around settled areas. Gaglioti and fellow researchers (2016) found that pre-industrial fire return intervals (based on soil charcoal deposits) ranged from 33-80 years ($\overline{x}$= 58 years, $P<0.05$, 40-77-year range) to 11 to 26 years ($\overline{x}$= 18 years, $P< 0.05$). The cause of this change in return intervals near populated areas is thought to be because of the increase in population in this region from 1940 until present and the subsequent increase in human caused fires (Gaglioti et. al. 2016; DeWilde & Chapin 2006). Calef (2015) found an 8.9% increase in areas burned that coincided with the shift into positive values for the PDO around 1976 (Calef et. al 2015). While this increase can be partly attributed to climatic factors, warmer temperatures since 1976 meant more human recreational activity in areas that that did not see much use due to either access issues or climate conditions that discouraged extended recreational use. Where human presence increases, unintentional fires tend to occur frequently (Calef et. al. 2015), and with landscape changes occurring from climate influences, human contributions may cause regional alteration even in areas of low population density (villages of 200 people or less with more than 50 km of separation).

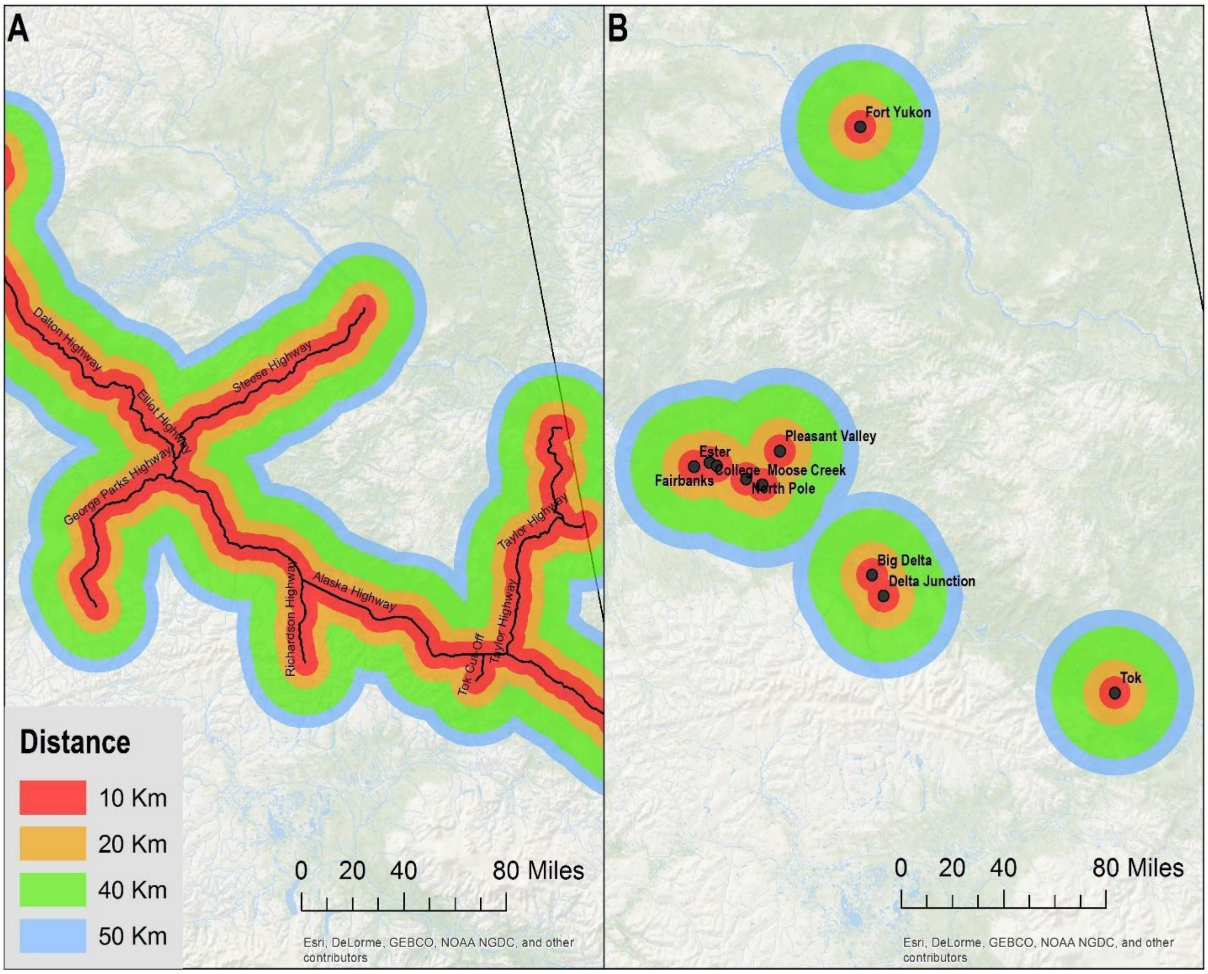


Figure 3-22: Buffer distances of 10, 20, 40, & 50 km around major regional roads and population areas. Areas within 10 km of roads (A) and population centers (B) are at the greatest risk of human ignitions, while green and blue bands indicate remote areas where fires tend to start from natural causes. The Richardson and Alaska Highways are the main roads in the region, and see the most use. Fires that begin on these roads are usually caused by negligence, or accidents, but are usually local in their effects. These are the only paved access routes in the region—no other roads or easily drivable trails exist. Not shown in this diagram are the isolated villages of Fort Yukon to the north and Galena which lies approximately 240 km north and west of Fairbanks Data: www.AKDOT.gov.

Human influences on regional wildfire stem primarily from accidental recreational fires that get out of control, but also from controlled burns that result in more acreage being consumed than originally planned (DeWilde & Chapin 2006). Consensus in the reviewed literature supports the conclusion that human ignitions accounted for the greatest number of fires within

10-20 20 km of populated areas (Figure 3-22) (DeWilde & Chapin 2006). Human caused ignitions also generally occur within these same distances of the major regional roadways (Johnson & Myanishi). Naturally occurring fires tend to occur at distances of greater than 20 km from major roads and populated areas.

The most common ignition source at these distances greater than 20 km is lightning strikes that occur because of larger and more frequent mid and late summer storms (a result of the transition into the positive phase of the PDO [Wendler & Shulski 2008] and increased atmospheric CO_2 concentrations). Human ignited fires alter the vegetative composition within these corridors because human started fires tend to occur earlier in the growing season (Kasischke et. al. 2006) thus successional trajectories have more time to divert toward novelty in vegetative composition (Shenoy et. al. 2011). Areas where human fires tend to occur because of accident correspond with recreational areas because many these areas fall within the 10-20 km distance thresholds of regional major roads and cities. Additionally, native peoples of the Yukon Flats area (Dendu Gwich'in [Natcher 2004]) have used fire as a means of land clearing—fires that sometimes get out of control and spread from areas where underbrush clearing is the goal to areas of boreal forest that get unintentionally burned. The effects of intentional and non-intentional fires and the effects these fires have on the human population of the region are discussed in Section 4.0.

Section 4.0- Discussion

There is both an anthropogenic and natural influence on the processes of fire and soil carbon emissions however, the most important consideration is the timing of these cycles considering current human population dynamics in Alaska. There is a consensus of the literature that climate induced changes in wildfire spatial distribution and occurrence, coupled with changes in the regional distribution and quantity of soil carbon, support the formation of an overall cyclical positive feedback loop that may cause future fire regime novelty. Warmer mean temperatures have caused an increase in the number and size of fires that have occurred since the 1950's, (McGuire et. al. 2009) and this will have pronounced influences on human settlements in the region, especially as post-fire successional trajectories favor deciduous dominated succession (Kasischke et. al. 2010). Since approximately 10,000 years ago (Johnson & Miyanishi 2012) there has been a human presence that relies heavily on the boreal region for provision of fish, game, and forest resources to survive and maintain their cultural identity. As climate change alters the regional fire and carbon cycles (Moritz et. al. 2012), human uses and influences will become increasingly important.

Soil Carbon Dynamics

Shifts in carbon cycling and fire regime will occur regionally if current observed trends continue to prevail. Novel fire cycles will directly affect the carbon cycle as increased SOC loss through combustion sends more greenhouse gasses into the polar region atmosphere supporting a positive warming feedback loop (Yuan et. al. 2012). Climate exerts regional control over soil carbon dynamics primarily through two pathways—the first being seasonality and the second being vegetative. Climatic shifts toward earlier springs and longer summers support more robust growth of endemic plant species with greater richness of biodiversity (Euskirchen 2009). Warmer summers support the growth of deciduous forests that replenish soil carbon faster than confers, and are less prone to severe fires (Johnstone et. al. 2010). Warmer temperatures also activate soil microbes (Boby et. al. 2010) that decompose surface organic material (initially increasing CH_4 outputs) that ultimately results in soil carbon level increases (Taş 2014; Field et. al. 2007). On the landscape and patch scales, fire exerts the strongest influence on soil carbon cycles by removing local pools of soil carbon and altering soil geochemistry. Fire also exposes mineral soils that favor deciduous recruitment in post-fire sites. At the patch and landscape level soil carbon cycles become intertwined in complex feedback loops as soil carbon that is burned in ground level fires increases atmospheric CO_2 (Prentice et. al. 2011). The increase in GHG emissions from fires supports increased climate warming while simultaneously fire alters vegetative composition, diversity, and phenology (Root 2003) that alters flammability profiles of forests that accumulate detritus that decomposes, eventually stabilizing carbon stocks. Additionally, longer and warmer summers favors the expansion of forest lands with increased landscape connectivity (Stavros et. al. 2014) or corridor creation that can turn the carbon pools of patches into landscape level carbon pools, and landscape connectivity affects regional carbon stocks (McKenzie et. al. 2004). New methods that are repeatable and fast (around a 60-minute processing time [Smith et. al. 2015]) for gauging ground layer soil carbon pools responses to ecosystem changes show promise in helping researchers understand the sparsely sampled soil carbon pool of the Arctic and Holarctic regions (Smith 2015). As will be discussed later in this section, this can help fill data gaps regarding soil carbon behavior over time (Birdsey et. al. 2009) and help researchers gauge how soil carbon is affected by both climate and fire, and whether these forces will act in concert to increase future regional emissions (Smith 2015).

Permafrost Dynamics

Climatic influences drive permafrost cycles on the regional scale—through longer warmer summers that keep continual depressive pressure on permafrost layers (Turetsky et. al. 2014). Regional permafrost dynamics influence on soil carbon stocks through climatically driven processes of degradation and aggradation will become more pronounced in a warmer summer climate (Jorgenson 2015), leading to spikes in soil carbon levels and patches becoming carbon sources, if warming trends continue (2015). Regionally, this is a relatively straightforward cycle that becomes more complex at the finer landscape and patch scales. Fire influences permafrost on patch scales (O'Donnell 2011) except where large, intense fires burn across smaller landscapes of the region—when these fires occur they can exert strong influences on permafrost, thus soil organic carbon by causing biogeochemical changes in surface horizons of soil.

At the landscape scale, particularly in areas where suppression is impractical, permafrost extents can be fragmented when sufficient loss of insulating surface carbon is lost and subsequent increases in radiative forcing melt or eliminate permafrost (Jorgenson 2015; Randerson et. al. 2006). The result is short term degradation of permafrost layers with subsequent liberation of previously frozen soil carbon stocks. Climate and fire both influence thermokarst and topographic deformation, and thermokarst can affect flora biodiversity in the short term (Lara et. al. 2016). The result is a semi monoculture of plant species that are specifically adapted to wetland soils. However, over time permafrost layers can recover as vegetation regrowth (adapted to the wetter environment of a collapse scar bog or muskeg) reforms an insulating organic carbon layer that protects active layers overlaying permafrost (Routh et. al. 2014).

Aside from the transformative effects of thermokarst processes on patch and landscape belowground soil carbon stocks, thermokarst processes will drastically alter above ground fuel sources as the region warms (provided current trends in climate shift continue unabated) (Tamocai et. al. 2009). As permafrost layers become increasingly stressed under warming conditions (Jorgenson 2015, Olefeldt 2016) forest stand structure is going to be negatively affected by surficial deformations caused by thermokarst. Forest stands will become increasingly at risk to tree loss as trees fall over when their root systems become compromised (Shenoy 2011) as surface layers subside and destabilize. Additionally, old growth conifer stands (with the highest flammability indices [Moritz et. al. 2012]) can become unstable as thermokarst progresses—a problem that can be remedied by timber harvesting that removes the older growth, higher flammability trees (Calef et. al. 2015). Permafrost retreat induced thermokarst will become in increasing important consideration, as a warming climate favors the expansion of forests into areas that were previously dominated by tundra (Johnson & Myanishi 2012; Tape et. al. 2016).

Successional Trajectory and Subsistence Species

Larger, more intense and severe fires are expected to occur in the coming century (Moritz et. al. 2012), and increased temperatures and decreased rain and snowfall are the driving factors in fire regime novelty (A. Young et. al. 2016). When fire activity increases, especially with favorable terrestrial conditions, carbon emissions increase that spur self-sustaining novel climate patterns (Field et. al. 2007). Perhaps the most complex regional cycle is that of succession and its influences on human communities. Fire influences successional trajectories as previously stated, and those successional trajectories favor either abundance of big game species, or it can limit herd member expansion (Tape 2016; Natcher 2007). Intense fires tend to favor successional trajectories toward an initial strong recruitment of shrubs and deciduous tree species, while more mild fires of lower intensity tend to favor black spruce recruitment with eventual stand replacement entirely of this species of conifer (Goetz et. al. 2007). As fires become more intense and severe (in terms of biogeochemical soil changes and black spruce mortality) the early recruitment of these shrubs and deciduous species (particularly birch and alder) favors growth of moose herds. Since moose primarily forage on these herbaceous species (Nelson et. al. 2008) the early recruitment of these plants favors higher rates of moose reproduction and greater instances of cows birthing twins (Nelson 2008). During early stages of succession when deciduous species are favored, natives and other Alaskan hunters will find greater subsistence resources that support all communities alike; especially since most residents of the region practice either total subsistence or semi-subsistence (primarily harvesting wild fish and game resources with minor produced product supplementation). Additionally, early successional trajectories that favor deciduous species also favors the recruitment of berries, mushrooms, and other food items widely foraged and used throughout the region. As temperatures warm and the boreal region expands to the north under increasingly favorable climatic conditions, the range of moose is anticipated to concurrently increase (Tape et. al. 2016) thus creating greater available subsistence resources as deciduous recruitment or muskeg and tundra transition into favorable ungulate forest land habitat (Tape 2016). This will be a positive development for regional residents as an abundance of game species provides economic relief to residents of isolated village communities who would otherwise have to spend scant financial resources acquiring processed rather than subsistence food resources.

Deciduous forest stands are more resistant to wildfires and this stability allows for these stands to progress into late deciduous dominant stands (provided initial burn severity was sufficient to favor such a trajectory) with a large quantity of ground level biomass (Goetz 2007). Late stage deciduous dominated forest stands favor the growth of mosses and lichens in both exposed areas or patches and meadows with minimal tree growth (Hu 2006). These comprise the primary food stuffs for herds of migratory caribou that seasonally travel through the boreal region to late summer breeding grounds (Natcher et. al. 2007). Caribou is the primary food source for many of the northwest arctic native groups such as the Iñupiat Eskimos and certain western Athabascan peoples, therefore forest compositions of predominantly deciduous stands with increased biomass of moss and lichens supports not only insulating ground layers that protect permafrost (Jorgenson 2015), but the forage requirements of larger caribou herds (Nelson 2008). Warmer, longer summers can induce phenological changes (Root 2003) to caribou mating behavior, pushing it to later periods in September rather than the current breeding season of late August- early September (Root et. al. 2003). Given that caribou generally are not harvested during the rut, this phenological change supports increased subsistence harvesting and although such hunting pressure may intuitively cause a critical decrease in the caribou herd, the increased volume of available food resources supports larger initial herd population and increased breeding success with lowered losses to winter starvation or predation (Nelson 2008).

Fish and waterfowl species constitute an important subsistence resource in addition to the terrestrial game species. The literature shows that while fires can alter the vegetative profiles of shore lines and riparian systems, there is very little affect to the water ways themselves, and thus minimal effect on aquatic vegetative species that waterfowl depend on for food (Lewis et. al.

2016). Aside from minor biogeochemical alterations to the soil that may result in a slight increase in aquatic nutrient concentrations or spikes in fresh water levels that correspond with slightly increased levels of snow melt and hydraulic conduction from increases permafrost fluctuations, aquatic environments generally show little response to fire events. Waterfowl populations are largely resilient to the effects of fire (Lewis et. al. 2016), except where dry periods may hinder the recovery of grasses and low-lying forbes that comprise the breeding and nesting habitat of these species. Generally, these effects are short lived and do not correspond to drastic waterfowl population fluctuations that are effected more by general climate patterns (Lewis 2016).

Fire is generally thought to be a destructive force (Johnson & Myanishi 2012; Lewis et. al. 2016) that causes landscapes to become homogenized through loss of vegetative biomass, however this is rarely the case. Fire can remove a large amount of soil carbon and above ground biomass, but throughout the literature the result in early successional stages are often patches of landscape delineated by greater initial biodiversity (if fires are not too severe [Bret-Harte 2013]). However, where fire does create a biomass monoculture (primarily conifer species) due to low intensity (the kind that generally result from human ignition) the regional fauna can suffer (Johnson & Miyanishi 2012). These species require a variable diet to successfully survive, and the second major effect of fire is opposite to fire induced species diversity. Where monoculture trends lead to patch and landscape homogeneity, big game species are less successful.

When low intensity fires favor the early successional recruitment of black spruce or white spruce (Wang & Kemball 2010), energy dense food sources that moose require while recovering from the long regional winters (Natcher et. al. 2007) are less abundant or their growth is suppressed by the fire adapted and relatively superior competition from spruce seedlings which constitute a poor food source (Nelson et. al. 2008). Late spring and early summer vegetative growth dominated by conifer species provides low nutrition browse that moose are not as efficient at utilizing. Because of this poor fodder, noticeable phenological changes in breeding occur—cows either do not enter estrus in normal cycles, or they will enter it later in the season after dominant bulls have mated resulting in either fewer, or less fit offspring (Kasischke et. al. 2010). This results in cows with only one or no calves, or calves that end up dying due to bear and wolf predation. This reduction in the population caused by fire induced changes to landscape vegetation forms a negative feedback to dependent human populations—less moose means less meat that subsistence communities have for their winter use. When this occurs, native communities are forced into more resource consumption from large population areas or isolated communities like Ft. Yukon or Galena may require emergency winter assistance.

Regions that are dominated by caribou generally do not suffer from fire related monoculture as the forest stands in those areas are mostly codominant mixed stands of aspen and spruce (Brown et. al. 2016). When spruce is favored, lichens and mosses tend to flourish providing feed for caribou. Being barren ground feeders, caribou are relatively resilient to fire effects as they generally avoid burned areas for decades post fire (Nelson, 2008; Lorianty et. al. 2014). Where fire homogenization can harm caribou herds, is when fire homogenizes lichen and moss composition toward species that lack the high fructose and high energy density that caribou depend upon (Bret-Harte et. al. 2013; Euskirchen et. al. 2009). Another way in which fire homogenization of landscape can affect caribou is when fire causes large amounts of downed trees or creates natural obstacles to caribou migration (caribou are prolific migrators—traveling up to 30-50 km in a day) that impede the herd's ability to travel from one feed patch to another. Generally, fire exerts only minor influences on caribou fecundity and therefore availability as a subsistence resource. Fire behavior has important and in some instances, critical, implications for the region. Data regarding fire location, size, behavior, and assumed soil carbon effects are key for informing intelligent management decisions, but these data are not without limitations.

Data Gaps, Spatial Modeling Limitations, and Influencing Factors

The NCSCD provides valuable data regarding soil carbon concentration at a regional and global scale and is useful in examination of the relationship between soil carbon concentration and thermokarst and when examined with permafrost extent, informs the relationship between carbon content and permafrost (areas of greater permafrost presence store larger quantities of soil carbon). The primary weakness of the NCSCD is a lack of a time aspect to the dataset. The data on soil carbon concentration is current as of 2013, however this data is not annually monitored. This limits statistical analyses that can be done with this data through ArcGIS® software—based on soil carbon concentrations in areas of fire perimeters assumptions need to be made about carbon behavior based on literature findings. Literature findings support the conclusion that more intense fires combust greater quantities of soil carbon, however, relationship quantification using parametric statistical tests is not possible because of a lack of annual data on changes in soil carbon concentrations or mass over time. The level of carbon loss due to fire in the literature is variable based on multiple dynamics of permafrost, seasonality of fire occurrence, native carbon stocks pre-fire, and climate influences. Additionally, the various models utilized in literature studies shows considerable variability based on the types of models used and those models' governing parameters. Generally, the literature agrees that low lying areas or areas near major rivers release the greatest quantities of carbon during fires as these areas are predominantly black spruce dominated forest stands, and have the largest quantity of above ground biomass (these are also the most fire prone areas). Carbon loss can be inferred from the data analyzed through ArcGIS®, however, literature review is necessary to provide some idea of carbon loss by mass. Soil carbon levels may be temporarily reduced by fire disturbance (Hurteau & Brooks 2011), but climatic factors most strongly influence soil carbon dynamics. Climate influences average temperatures and the length of growing seasons for terrestrial biomass (Wendler & Shulski 2009), and warmer longer summers favor the accumulation of biomass that replenishes soil carbon layers over time (Boby 2010; Yiqi Luo 2007). Warmer temperatures drive permafrost layers deeper which increases microbial decomposition of detritus (Boby 2010). Fire's influence on soil carbon is exerted through successional trajectories that favor deciduous forest stands that deposit more detritus through seasonal loss of tree leaves (conifers do not loose needles at similar rates).

Thermokarst data is very limited in its analytical potential. Olefeldt and fellow researchers (2016) used the NCSCD to identify areas where thermokarst regionally occurs based on soil carbon mass, however the dataset would greatly benefit from measurements of landscape deformation based on satellite data that monitor the progress of topographical depression or other changes. This dataset would also benefit from a temporal factor just as the NCSCD data—addition of this field to the dataset would allow for analysis of the rate of thermokarst related landscape change and would thus support predictive conclusions of which areas are the most susceptible to landscape change with subsequent changes in patch level carbon concentrations. The literature shows that thermokarst rates are both climatically and disturbance influenced—patch areas in tundra and forest where large fires occur experience albedo changes (Mack et. al. 2011) that allow greater radiative forcing (Randerson 2006) that causes temporary permafrost retreat and ice wedge destabilization with subsequent land deformation (Jorgenson 2015). Long term thermokarst that causes regional permanent landscape deformation is dependent on higher mean annual temperatures in the region, since it is largely mean temperatures that determine permafrost content and retreat.

Permafrost extents when geoprocessed show both the range of extent classifications and the soil carbon levels within these extents. As Figure 3-5 illustrated, the isolated regional extents contained the greatest quantities of carbon since this extent is the most active in freezing and thawing cycles. As with thermokarst areas, permafrost levels at the patch level are disturbance influenced; fires degrade carbon layers that in turn alters radiative forcing causing active layer destabilization and temporary permafrost retreat. On the regional scale, climatic influences, primarily increased temperatures, are what determines the dynamics of permafrost aggradation or degradation. This dataset would benefit from attributes showing both the level of permafrost increase or decrease within the surveyed layer, and a time aspect to survey measurements that would support simple parametric statistical analyses of change in layer depth over time. This would support both geospatial analysis of permafrost levels as climatically influenced, and analysis of fire's relationship to permafrost on both patch and regional scales. This would inform how fire dynamics will change patch permafrost levels and the projected rates of permafrost level shrinkage and recovery, and whether fires cause clustering in patterns of loss on a regional scale or whether fire's affects would be random throughout a spatial plane.

Regional fire data are generally reliable for analyses using ArcGIS® software, and show random regional distribution throughout the boreal area from 1942-present. The concentration of large perimeter fires tends toward the western portion of the region corresponding with areas of biomass concentration in uninhabited or sparsely inhabited areas. Fires are almost completely climatically influenced in their rates of occurrence, but fire size influenced by a combination of climate, vegetation, topography, and seasonality. The literature indicates that spruce dominated areas experience the highest post-fire tree mortality (severity) and highest intensity fires, especially if ground fires in these areas become canopy fires. Fire perimeters in this dataset prior to 1990 are based on historical records and therefore the reporting may not be as accurate as recent (later than 2000) data that were collected from satellite imagery and delineated using fire modelling software. The data have both spatial and temporal aspects which allow for predictive statistical analyses, and coupled with literature synthesis show that fire occurrence will be most directly influenced by climate in the coming century. Generally, forest composition determines carbon emissions and determines fire severity and intensity. Black spruce stands emit the most carbon even though they may be smaller in area than stands dominated by white spruce and aspen (the predominant forest composition after black spruce). These forest stands are more flammable so if these types of stands become dominant they will increase carbon emissions dramatically as temperatures warm and drive more frequent large fire seasons. These stands support both ground and canopy fires where deciduous or deciduous conifer mixes tend to support more canopy level fires with lower carbon emissions than ground fires. Additionally, thermokarst transformations will result in greater loads of ground level fuel buildup should this process occur under coniferous dominated forest stands—build up that will need to be removed to prevent greater future fire emissions.

Significant Counter-Findings

Some of the literature (particularly literature studying Holocene patterns) indicate that the carbon and fire cycles spoken of in this paper are natural—they occur approximately every 5-10,000 years in this region (Kelley et. al. 2013; Johnson et. al. 2012). Paleo records indicate that similar cycles to what is being observed now occurred during the Holocene period. Charcoal records examined by some researchers (Kelley 2013; Ding 2015) indicate that severe fires occurred in the region 3-5,000 years ago and that large quantities of black spruce forest stands were lost. Currently observed cycles of deciduous succession were observed with the result that succession progressed through phases of deciduous domination, then mixed forest stand, with black and white spruce stands eventually becoming dominant and soil carbon levels becoming stable over a 2-3,000-year period (O'Donnell 2009). Much of the literature indicates that regional carbon levels are cyclical over a 3-5,000-year period and although influenced by disturbance, eventually they stabilize within the millennial timeframe. Climate drives vegetation fecundity and therefore warm periods favor biomass density that was somewhat greater during past regional warming phases (Allen et. al. 2010). Soil carbon build up is a process of plant life cycles, detritus decay, and natural surface and active layer freezing that causes carbon to accumulate over time that stabilizes during cold periods where the active layer becomes shallow and permafrost aggrades (Jorgensen et. al. 2015). Ice wedges that stabilize permafrost also increase in size and volume during colder periods and this stabilizes ambient soil carbon mass. Surface drying that occurred during past warm periods and soil hydrological changes only affect the top most soil layers, as over time deeper soil layers (greater than 10 cm) gain moisture content (Prentice 2011). Soil carbon layers are minimally influenced on a regional scale by human activities since humans tend to congregate in small scale settlements (Natcher 2007). The native climate is conducive to only small scale agricultural production, usually in the form of private or community gardens, so human activities that drastically alter carbon cycles in lower latitudes do not occur in this region.

Summer temperatures cause a spike in permafrost level decline, but when observed over the entire year declines are minimal during shorter timescales (Davidson & Janssens 2006). The ice wedges that stabilize carbon levels also stabilize permafrost layers with a resultant recovery of permafrost levels (Jorgenson 2015). Areas where permafrost is isolated or sporadic, may experience a slightly increased influence from fires, and small scale increases in carbon emissions from fire, but the overall regional permafrost profile does not experience a marked influence from fires, even very large ones (Jorgenson 2008). As these areas of permafrost recover, they will exert a stabilizing influence on carbon levels that will be less susceptible over time from fire combustion, thus reducing net carbon emissions. Furthermore, thermokarst influenced areas can recover to pre-thaw conditions as permafrost layers regenerate and frost heaving restores local and regional topography (Jorgenson 2015; Bachelet 2005).

Novel fire regimes are a result of climate interactions, and they eventually stabilize. Generally, the literature indicates that fire activity increases during warm periods but eventually vegetative influences governed by climate cause the return interval to stabilize. As initial spikes in fire consume flammable biomass, successional trajectories that favor fire resistant forest stands, or simply a loss of available fuel load, return fire intervals to the observed norm of around 300 years for aggressive fire seasons (Kasischke 2010). In the short-term fire emissions have the potential to create a positive feedback loop, but over the long term (periods of greater than 1000 years) this feedback loop is stabilized by increases in vegetation that “scrub” CO_2 through photosynthesis metabolism (Prentice & Harrison 2009). Carbon emissions from fire decrease in regions where topographical changes have resulted in collapse scar bogs or muskeg as these landscapes are not fire prone because of high soil moisture. Also, the PDO will transition back to the negative causing decreased temperatures and subsequent reduced risk of large, frequent, or intense wildfire events.

Regional Significance

Currently the population of Alaska has increased 56% from 1980 until 2010 (www.census.gov) and this influx of human population will continue to use land resources susceptible to fire influences. Increased human populations mean increased land use for commercial, domestic, or recreational purposes, and these increases translate to more frequent human caused fire ignitions in the coming decades (Johnson & Myanishi 2012). The effects of fire induced carbon emissions are not limited to just the boreal region of Alaska—these fire events and carbon cycles occur in other circumpolar climes in Canada, Scandinavia, and Russia (Allen et. al. 2010). The larger problem to consider is that atmospheric carbon concentrations are reaching levels that may be difficult or impossible for plant life to remove through photosynthesis alone. When these emissions are considered against increasing global deforestation rates in critical carbon sinks such as the Amazon Rain Forest, or the rain forests of Southeast Asia, it becomes clear that reliance on natural biotic process to maintain atmospheric CO_2 balance may become impractical in the future (Allen 2010). Arctic positive feedback loops may become more permanent over time requiring drastic changes in lifestyle, regional resource use, and livability for human populations.

Fire suppression, while well intentioned, seems to do more harm than good in the near term by encouraging monoculture in native forest stands and increased volumes of floor level fuels (Chapin et. al. 2003; Gaglioti et. al. 2016). The policy of total fire suppression has caused a considerable accumulation of dense undergrowth and "dead and down" fuels and increases area fire risks around human population centers (Calef et. al. 2008). When fires ignite in these areas they can cause both high mortality canopy fires (more tree loss) and carbon burning ground fires (altered soil carbon content) with a degradation of subsistence resources previously spoken of (Natcher 2007). Unless measures are taken to more effectively manage forest stands toward minimalized flammability under a new and novel fire regimen, the flora biodiversity that supports increases in regional megafauna populations will be lacking resulting in fewer moose and caribou. The result of inadequate forest and fire management will cause this region to suffer physically and economically. This need requires policy changes to adequately manage all regional forest resources for abundance.

Section 5.0- Recommendations

Climate induced novelty in regional fire regimes that support frequent, intense and severe fires that burn greater quantities of soil carbon in ground level fires is pushing a positive feedback loop that may sustain fire regime and carbon cycle novelty into the 21st century while Alaska's total population is steadily increasing. Based on the high probability of future fire regime novelty, and the increased population that will require boreal region ecosystem services to thrive, certain land use recommendations should be considered. Based upon the discussion in Section 4.0, my recommendations as informed by the evidence presented in Section 3.0, focus on three primary areas—fire suppression policies, forestry management and human uses, and data needs.

1. Fire Suppression Policies/ Actions
    - *Limit fire suppression activities to only that which is necessary to preserve life and property within the 10-km buffer zone around habited areas and near roadways (fires closer than 10 km should be managed as they currently are).*
    - *Utilize community resources and technology in fire spotting and suppression activities.*

The data and literature both support the conclusion that fire suppression in areas marked as critical and full suppression experience a buildup ground level fuels over time. My recommendations for fire suppression around populated areas is one of decreased suppression activity. In populated areas, fire suppression is necessary to protect life and property, however, in surrounding areas, demarcated by a 10-km buffer zone, minimal interference with the natural fire cycle is more appropriate. Fire suppression activities should focus on maintaining a minimum perimeter of 5 km around towns or areas where there are more than 100 people per km^2 to protect property and human life or livelihood. In areas outside of that 5-km buffer, small fires should be closely monitored with responders standing by to act as necessary. In areas outside of the 10-km buffer zone fire management should be on an as needed basis- many of these areas are remote and access will be difficult, therefore allowing these fires to burn is the most economically viable and ecologically sound policy. Areal monitoring of these fires is practical and necessary to ensure that they do not spread to the 10-km buffer zone—if they do then management policies should be implemented. Fires that burn in areas greater than 40 km away from populated areas should not receive firefighting or other suppression resources, however, where these distances correspond to remote recreational or federally recognized subsistence hunting/ fishing areas, human presence in these locations at the time of the fire should be assessed appropriately.

I believe it necessary to encourage universal community involvement in both the discussion on, and implementation of these policies. Public meetings between native and non-native community groups to both discuss the most effective and universally beneficial fire restriction plans and implementation strategies should be encouraged, as this sometimes does not occur in the region (federal forest service personnel usually implement policy with minimal public input). It will be beneficial to garner public support and involvement by creating volunteer forest fire fighting brigades, and to encourage the use of technology to increase the effectiveness of these units in spotting and fighting fires within the management buffer zone (10 km or less distance from roads and towns). Local UAV (unmanned aerial vehicle or drone) operators can be encouraged to support state fire fighters through use of their UAV's to provide real time fire monitoring of location, size, and direction of spread. While there may not be a regional budget to support such brigades, tax incentives in the form of a 2-3% contribution based property tax reduction could be instituted for those who actively participate in community based fire management activities. Fires outside of the active management perimeter can be monitored by these UAV operators to inform state firefighting agencies if these fires are encroaching on the management zone—if they are not they should be allowed to burn naturally (carbon emissions may spike, but they will stabilize and decrease over a period of 30-100 years per the literature).

2. Forestry Management/ Land Use Changes

- *Relax timber harvesting restrictions in 5-20 km zones around populated areas and near roadways and simplify and streamline the efficiency of the personal use timber harvesting permits within these areas.*
- *Modify land use of recreational areas to restrict post-burn access, and utilize local and traditional knowledge to both recover and manage burned forest areas.*

Currently, the State of Alaska has relatively complicated laws regarding timber harvesting throughout the state. Permitting is required to harvest living timber or "dead and down" timber in many areas for fire wood or small scale construction use. To reduce the fuel loads in these areas, I recommend easing the timber harvest permitting requirements for residents of the region. Unrestricted harvesting of dead and down timber in all areas of the region should be encouraged, and to prevent abuse of the practice, should be conducted with locally appointed or elected harvest monitors. If regional residents own large tracts of land, or their land is adjacent to state public lands, a previously agreed upon buffer zone in state lands should be provided for unrestricted use by the neighboring land holder. In populated areas, complete removal of dead and down should be encouraged by residents who wish to burn firewood during the winter rather than heating oil.

Where forest stands are aged, permissive policies for removing old, and potentially increased fire hazard trees should be encouraged. Rather than requiring expensive and restrictive permitting, allow regional residents to remove predesignated members of extant forest stands with the timber harvest monitor's supervision to ensure only the marked trees are taken. Also, in areas where thermokarst has caused "drunken trees" (trees that have partially fallen over due to loss of soil integrity), these trees should be allowed to be harvested without permit to prevent them from contributing to stocks of dead and down that can become unmanageable over time. Comprehensive yearly monitoring by terrestrial based personnel and areal satellite can identify where areas of thermokarst have caused large stands of drunken trees and these areas can be listed as high priority for unrestricted timber harvesting to prevent excess detritus and fuel pool accumulation. Additionally, forest surveys using the latest LiDAR technology can assist forest managers in creating a dynamic, rotating database to identify those areas where forest population may require permitting to restrict harvest, and those areas where unpermitted harvest are necessary to clear out the area prior to it becoming a high fire risk area.

When areas are subjected to influences of increased fire activity, it is necessary to address human land use factors to preserve the recovering ecosystem until it returns to a stable state. For this purpose, I recommend limiting access to recreational areas or remote areas where significant fires have burned. Depending on the level of biomass loss, human use of off road vehicles, horses, or foot traffic should be strongly discouraged to prevent both surface soil loss to erosion, and to minimize the risk of fire reignitions from disturbance of holdover fire layers. This may cause some community resistance if these fires have occurred in areas where traditional subsistence hunting or fishing activities are seasonally practiced, however, as stated incorporating greater community involvement in land use management will alleviate tension between regulators and the public. Just as involving the community in pre-fire planning can increase the community's stake in preservation of landscape ecological health, so can post-fire inclusion in management decisions encourage public stewardship of burned areas. Limitations on access should be reasonable without being excessive—a decision that will require a case by case analysis of the extent of biomass loss from fires throughout the region. Residents who wish to conduct subsistence foraging and hunting activities should do so once it is assured that fires are more than 90% contained or extinguished.

There is a great deal of traditional knowledge to be found within subsistence and native communities and that knowledge should be sought after aggressively by forest managers and regulators alike. The encouragement of “citizen science” with such experience will bring not only a sense of cooperation between interested parties, it will encourage the incorporation of traditional knowledge gained by millennia of residency into the pool of peer reviewed traditional academic science. These two pools of knowledge can then be collectively applied to all management aspects of the boreal region’s forests to ensure the highest degree of forest recovery and maximal preservation of ecosystem services. Such preservation will also have a mitigatory effect on carbon emissions as sound, case by case application of these management principles will encourage speedy forest stand recovery that stabilizes soil carbon levels over time and encourages forest stands that can “scrub” atmospheric CO_2 concentrations reducing the effect of the positive feedback loop.

Encouraging fewer outdoor fires through regulation is one component of effective fire and thus soil carbon output management, however, it will only do so much to address the problem. Penalties for non-compliance with burn restrictions may be necessary to prevent home and land owners from violation of the restrictions. Increased liability for response and firefighting costs may be necessary in instances of the most egregious disregards for burn restrictions. If such fires originate on native corporation lands, then joint assessment of fines and fees should be conducted by both representatives of the corporation and non-native communities to address loss of property or resources due to casual and thoughtless ignition of fires by private parties.

3. Ongoing Monitoring & Data Needs

- *The NCSCD should be annually updated with both carbon concentration and mass data to track carbon changes on an annual basis.*
- *permafrost levels should be monitored annually to show annual levels of retreat or aggradation and thermokarst data should include annual measurements of surface subsidence.*

Data regarding the interaction of wildfire and soil carbon emissions is lacking, and has only recently been addressed through research aimed at understanding this dynamic. Federal funding encouraging more research into the influence of fire on soil carbon is necessary to fill data gaps in the understanding of this relationship. Ongoing monitoring of soil carbon levels in the NCSCD will provide temporal data that can show how these carbon levels fluctuate on a monthly and yearly basis. Satellite data and LiDAR technologies should be used to monitor thermokarst events and show not only a decrease or increase in surface elevation, but when those events occur to track landscape deformation over time. Coupling these data in comprehensive analyses will inform conclusions and thus decisions on the best management strategies on decadal time scales into the future. Finally, quarterly monitoring of permafrost levels throughout all regional extents would be very useful in informing not just the fluctuation of permafrost levels, but the likelihood of thermokarst processes initiating in areas where permafrost is showing the largest degree of fluctuation over time.

Section 6.0- Conclusions

Wildfire regimes in the boreal forest region are an interwoven web of naturally occurring terrestrial and climatic cycles. Permafrost interreacts with subsurface soils to both stabilize, generate, and regenerate (post-fire) carbon stocks within the boreal region that can act as fuel for fires and nutrient stores for boreal vegetation. When permafrost levels increase, soil carbon stocks become cryogenically stabilized and decomposition halts resulting in static levels of soil carbon. When permafrost retreats either through fire or climate disturbances, soil carbon stocks increase (due to decomposition) and become vulnerable to greater levels of fire activity. Retreating permafrost can cause landscape deformation (thermokarst) that results in novel soil hydrology, nutrient deposition, and novel surface biomass composition. Coupled with weather anomalies discussed in Section 3.0, this can drive novelty in successional trajectory, or favor biomass composition that increases surface deposition of future potentially labile carbon pools.

The fire regime in the boreal region is largely influenced by climate, although on patch and smaller landscape scales, the regime is strongly influenced by vegetation composition and topography. Longer warmer summers tend to favor fires that burn longer and later, and where forest stands are dominated by black spruce, severe fires tend to occur with subsequent higher carbon emissions. Severe fires ultimately act to increase fire return interval and decrease fire intensity by burning away surface soil carbon layers exposing underlying mineral soils that favor the recruitment of deciduous tree species. Deciduous dominated stands are less flammable than conifer stands so when fires do occur, they are of lower intensity which eventually favors the return of conifer dominated stands that are adapted to lower intensity fires. Once these forest stands become mixed codominant stands, carbon emissions reduce as a product of fire regimes that evolve from novel to those regimes that are considered “normal” in the region, and the cycle stabilizes (over centurial to millennial timescales).

Climate strongly influences forest composition, but it also exerts a pronounced influence on forest extent, and when coupled with fire influences that alter the biogeochemistry of regional soils, may lead to an expansion of the boreal forest that has not been previously seen. Where climate warming favors fires in tundra landscapes in the northern sector of the boreal region, forests can expand into areas that were previously grass and forb dominated peatlands. This can be a beneficial development as it expands the range of game species that residents subsist on, and some may argue that it creates a new category of intrinsic value to these lands. The negative development of novel forest expansion and colonization is twofold: it changes the fire dynamic of peat dominated areas (thus making the landscape more vulnerable to becoming a carbon source), and it can open corridors for fires to spread even further north into Arctic regions that are not adapted to semi regular or regular fire regimes. The result of such and expansion could be the catalyst for the entire region becoming a future carbon source that fuels a permanent positive feedback loop between fire, CO_2 emissions, and steady climate warming.

Humans continue to rely on the ecosystem services of the boreal forest in much the same way they have for the last 10,000 years. Human activities influence fires and related carbon emissions on landscape scales, and as the boreal region population grows, eventually human activity may affect fire and carbon emissions on the regional level. Human agricultural and industrial activity has changed the profile of the boreal region; opening corridors where none previously existed, creating fragmentation where there was once consistent forest landscape, and providing the means for fire to spread to previously invulnerable areas (with the associated carbon emission increases). Because of the potential for humans to drastically alter this region, great care must be taken to preserve the integrity of the region. The boreal forest region of Alaska is a truly unique ecosystem—a complex and intricate one that is as fragile as it is resilient. By implementing the aforementioned simple, straightforward management policies this region will continue to prosper and continue to sustain the plant, animal, and human communities found therein for centuries to come.

References Cited:

Abatzoglou, J. T., and C. A. Kolden. 2011. Relative importance of weather and climate on wildfire growth in interior Alaska. International Journal of Wildland Fire **20**: 479–486.

Allen, C. D., A. K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D. D. Breshears, E. H. (Ted) Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J. H. Lim, G. Allard, S. W. Running, A. Semerci, N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management **259**: 660–684.

Bachelet, D., J. M. Lenihan, C. Daly, R. P. Neilson, D. S. Ojima, and W. J. Parton. 2001. MC1 : A dynamic vegetation model for estimating the distribution of vegetation and associated ecosystem fluxes of carbon, nutrients, and water. Technical Documentation. Version 1.0. Page Gen. Tech. Rep. PNW-GTR-508. Pacific Northwest Research Station, Portland, OR. 97205.

Bachelet, D., J. Lenihan, R. Neilson, R. Drapek, and T. Kittel. 2005. Simulating the response of natural ecosystems nd their fire regimes to climatic variability in Alaska. Canadian Journal of Forest Research **35**: 2244–2257.

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

Barnhart, W. D. 2014. InSAR detects increase in surface subsidence caused by an Arctic tundra fire. Geophysical Research Letters **41**: 3906–3913.

Beck, P. S. A., S. J. Goetz, M. C. Mack, H. D. Alexander, Y. Jin, J. T. Randerson, and M. M. Loranty. 2011. The impacts and implications of an intensifying fire regime on Alaskan boreal forest composition and albedo. Global Change Biology **17**: 2853–2866.

Benali, A., A. Russo, A. C. L. Sá, R. M. S. Pinto, O. Price, N. Koutsias, and J. M. C. Pereira. 2016. Determining fire dates and locating ignition points with satellite data. Remote Sensing **8**: 1–20. DOI: 10.3390/rs8040326.

Birdsey, R., Bates, N., Behrenfeld, M., Davis, K., Doney, S. C., Feely, R., Hansell, D., Heath, L., Kasischke, E., Kheshgi, H., Law, B., Lee, C., McGuire, D., Raymond, P., Tucker, C. J. 2009. Carbon cycle observations: gaps threaten climate mitigation policies. EOS **90**: 292–293.

Boby, L. A., E. A. G. Schuur, M. C. Mack, D. Verbyla, and J. F. Johnstone. 2010. Quantifying fire severity, carbon, and nitrogen emissions in Alaska's boreal forest. Ecological Applications **20**: 1633–1647.

Bond-Lamberty, B., S. D. Peckham, D. E. Ahl, and S. T. Gower. 2007. Fire as the dominant driver of central Canadian boreal forest carbon balance. Nature **450**: 89–92.

Bond-Lamberty, B., A. V. Rocha, K. Calvin, B. Holmes, C. Wang, and M. L. Goulden. 2014. Disturbance legacies and climate jointly drive tree growth and mortality in an intensively studied boreal forest. Global Change Biology **20**: 216–227.

Bret-Harte, M. S., M. C. Mack, G. R. Shaver, D. C. Huebner, M. Johnston, C. A. Mojica, C. Pizano, and J. A. Reiskind. 2013. The response of Arctic vegetation and soils following an unusually severe tundra fire. Philosophical Transactions of the Royal Society of London. Series B, Biological sciences **368**: 1–15. DOI: 10.1098/rstb.2012.0490.

Brown, D. R. N., M. T. Jorgenson, T. A. Douglas, V. E. Romanovsky, K. Kielland, C. Hiemstra, E. S. Euskirchen, and R. W. Ruess. 2015. Interactive effects of wildfire and climate on permafrost degradation in Alaskan lowland forests. Journal of Geophysical Research: Biogeosciences **120**: 1619–1637.

Brown, D. R. N., M. T. Jorgenson, K. Kielland, D. L. Verbyla, A. Prakash, and J. C. Koch. 2016. Landscape effects of wildfire on permafrost distribution in interior Alaska derived from remote sensing. Remote Sensing **8**: 1–22. DOI: 10.3390/rs8080654.

Calef, M. P., A. D. McGuire, and F. S. Chapin. 2008. Human influences on wildfire in alaska from 1988 through 2005: an analysis of the spatial patterns of human impacts. Earth Interactions **12**: 1–18. DOI: 10.1175/2007EI220.1.

Calef, M. P., A. Varvak, A. D. McGuire, F. S. Chapin III, and K. B. Reinhold. 2015. Recent changes in annual area burned in interior Alaska: the impact of fire management. Earth Interactions **19**: 1–17. DOI: 10.1175/EI-D-14-0025.1.

Chapin, F. S., T. S. Rupp, A. M. Starfield, L. O. DeWilde, E. S. Zavaleta, N. Fresco, J. Henkelman, and A. D. McGuire. 2003. Planning for resilience: modeling change in human-fire interactions in the Alaskan boreal forest. Frontiers in Ecology and the Environment **1**: 255–261.

Damoah, R., N. Spichtinger, R. Servranckx, M. Fromm, E. W. Eloranta, I. A. Razenkov, P. James, M. Shulski, C. Forster, and A. Stohl. 2006. A case study of pyro-convection using transport model and remote sensing data. Atmospheric Chemistry and Physics **6**: 173–185.

Dash, C. B., J. M. Fraterrigo, and F. S. Hu. 2016. Land cover influences boreal-forest fire responses to climate change: geospatial analysis of historical records from Alaska. Landscape Ecology **31**: 1–13.

Davidson, E. A., I. A. Janssens. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature **440**: 165–73.

DeWilde, L., and F. S. Chapin. 2006. Human impacts on the fire regime of interior Alaska: Interactions among fuels, ignition sources, and fire suppression. Ecosystems **9**: 1342–1353.

Ding, Y., Y. Yamashita, J. Jones, R. Jaffé. 2015. Dissolved black carbon in boreal forest and glacial rivers of central Alaska: assessment of biomass burning versus anthropogenic sources. Biogeochemistry **123**: 15–25.

Escuin, S., R. Navarro, and P. Fernández. 2008. Fire severity assessment by using NBR (Normalized Burn Ratio) and NDVI (Normalized Difference Vegetation Index) derived from LANDSAT TM/ETM images. International Journal of Remote Sensing **29**: 1053–1073.

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

Field, C., D. Lobell, H. Peters, N. Chiariello. 2007. Feedbacks of terrestrial ecosystems to climate change. The Annual Review of Environment and Resources **32**: 1–29. DOI: 10.1146/annurev.energy.32.053006.141119.

Flannigan, M. D., M. A. Krawchuk, W. J. DeGroot, M. B. Wotton, L. M. Gowman. 2009. Implications of changing climate for global wildland fire. International Journal of Wildland Fire **18**: 483–507.

Gaglioti, B. V, D. H. Mann, B. M. Jones, M. J. Wooller, B. P. Finney. 2016. High-resolution records detect human-caused changes to the boreal forest wildfire regime in interior Alaska. Holocene **26**: 1064–1074.

Goetz, S. J., M. C. Mack, K. R. Gurney, J. T. Randerson, R. A. Houghton. 2007. Ecosystem responses to recent climate change and fire disturbance at northern high latitudes: observations and model results contrasting northern Eurasia and North America. Environmental Research Letters **2**: 1–9. DOI: 10.1088/1748-9326/2/4/045031.

Harden, J. W., S. E. Trumbore, B. J. Stocks, A. Hirsch, S. T. Gower, K. P. O'Neill, and E. S. Kasischke. 2000. The role of fire in the boreal carbon budget. Global Change Biology **6**: 174–184.

Hartmann, B., and G. Wendler. 2005. The significance of the 1976 Pacific climate shift in the climatology of Alaska. Journal of Climate **18**: 4824–4839.

Hu, F. S., L. B. Brubaker, D. G. Gavin, P. E. Higuera, J. A. Lynch, T. S. Rupp, and W. Tinner. 2006. How climate and vegetation influence the fire regime of the Alaskan boreal biome: The Holocene perspective. Mitigation and Adaptation Strategies for Global Change **11**: 829–846.

Hurteau, M. D., and M. L. Brooks. 2011. Short- and Long-term effects of fire on carbon in US dry temperate forest systems. BioScience **61**: 139–146.

Jain, T. B., D. S. Pilliod, R. T. Graham, L. B. Lentile, and J. E. Sandquist. 2012. Index for characterizing post-fire soil environments in temperate coniferous forests. Forests **3**: 445–466.

Jiang, Y., A. V Rocha, J. a O’Donnell, J. a Drysdale, E. B. Rastetter, G. R. Shaver, and Q. Zhuang. 2015. Contrasting soil thermal responses to fire in Alaska tundra and boreal forest. Journal of Geophysical Research: Earth Surface **120**: 363–378.

Johnson, E. A., K. Miyanishi. 2012. The boreal forest as a cultural landscape. Annals of the New York Academy of Sciences **1249**: 151–165.

Johnstone, J. F., T. N. Hollingsworth, F. S. Chapin, and M. C. Mack. 2010. Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. Global Change Biology **16**: 1281–1295.

Jones, C., C. McConnell, K. Coleman, P. Cox, P. Falloon, D. Jenkinson, and D. Powlson. 2005. Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil. Global Change Biology **11**: 154–166.

Jorgenson, M. T., M. Kanevskiy, Y. Shur, N. Moskalenko, D. R. N. Brown, K. Wickland, R. Striegl, J. Koch, M. Kanevskiy, Y. Shur, N. Moskalenko, D. R. N. Brown, K. Wickland, R. Striegl, and J. Koch. 2015. Role of ground ice dynamics and ecological feedbacks in recent ice wedge degradation and stabilization. Journal of Geophysical Research: Earth Surface **120**: 2280–2297.

Kaplan, J. O., I.C. Prentice, W. Knorr, P. J. Valdes. 2002. Modeling the dynamics of terrestrial carbon storage since the last glacial maximum. Geophysical Research Letters **29**: 10–13.

Kasischke, E. S., and M. R. Turetsky. 2006. Recent changes in the fire regime across the North American boreal region - Spatial and temporal patterns of burning across Canada and Alaska. Geophysical Research Letters **33**: 1-5. DOI: 10.1029/2006GL025677.

Kasischke, E. S., D. L. Verbyla, T. S. Rupp, a. D. McGuire, K. a. Murphy, R. Jandt, J. L. Barnes, E. E. Hoy, P. a. Duffy, M. Calef, and M. R. Turetsky. 2010. Alaska's changing fire regime — implications for the vulnerability of its boreal forests. Canadian Journal of Forest Research **40**: 1313–1324.

Keeley, J. E. 2009. Fire intensity, fire severity and burn severity: A brief review and suggested usage. International Journal of Wildland Fire **18**: 116–126.

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

Kolden, C. A., and J. T. Abatzoglou. 2012. Wildfire consumption and interannual impacts by land cover in Alaskan boreal forest. Fire Ecology **8**: 98–114.

Lara, M. J., H. Genet, A. D. Mcguire, E. S. Euskirchen, Y. Zhang, D. R. N. Brown, M. T. Jorgenson, V. Romanovsky, A. Breen, and W. R. Bolton. 2016. Thermokarst rates intensify due to climate change and forest fragmentation in an Alaskan boreal forest lowland. Global Change Biology **22**: 816–829.

Lawrence, D. M., and A. G. Slater. 2005. A projection of severe near-surface permafrost degradation during the 21st century. Geophysical Research Letters **32**: 1–5. DOI: 10.1029/2005GL025080.

Johnson, E. A., K. Miyanishi. 2012. The boreal forest as a cultural landscape. Annals of the New York Academy of Sciences **1249**: 151–165.

Liu, Y., S. Goodrick, and W. Heilman. 2014. Wildland fire emissions, carbon, and climate: wildfire-climate interactions. Forest Ecology and Management **317**: 80–96.

Lloyd, A. H., A. E. Wilson, C. L. Fastie, and R. M. Landis. 2005. Population dynamics of black spruce and white spruce near the arctic tree line in the southern Brooks Range, Alaska. Canadian Journal of Forest Research **35**: 2073–2081.

Luo, Y. 2007. Terrestrial carbon–cycle feedback to climate carming. Annual Review of Ecology, Evolution, and Systematics **38**: 683–712.

Mack, M. C., M. S. Bret-Harte, T. N. Hollingsworth, R. R. Jandt, E. a G. Schuur, G. R. Shaver, and D. L. Verbyla. 2011. Carbon loss from an unprecedented Arctic tundra wildfire. Nature **475**: 489–92.

Mack, M. C., E. A. Schuur, M. S. Bret-Harte, G. R. Shaver, and F. S. Chapin III. 2004. Ecosystem carbon storage in arctic tundra reduced by long-term nutrient fertilization. Nature **431**: 440–443.

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

McKenzie, D., Z. Gedalof, D. L. Peterson, and P. Mote. 2004. Climatic change , wildfire , and conservation. Conservation Biology **18**: 890–902.

Michael M. Loranty, Susan M. Natali, Logan T. Berner, Scott J. Goetz, Robert M. Holmes, Sergei P. Davydov, Nikita S. Zimov, S. A. Z. 2014. Siberian tundra ecosystem vegetation and carbon stocks four decades after wildfire. Journal of Geophysical Research : Biogeoscience **119**: 2144–2154.

Miquelajauregui, Y., S. G. Cumming, and S. Gauthier. 2016. Modelling variable fire severity in boreal forests: Effects of fire intensity and stand structure. PLoS ONE **11**:1–24. DOI: 10.1371/journal.pone.0150073.

Miyanishi, K., S. R. J. Bridge, and E. a. Johnson. 2002. Wildfire regime in the boreal forest - Reply. Conservation Biology **16**: 1177–1178.

Moritz, M., M.-A. Parisien, E. Batllori, M. a. Krawchuk, J. Van Dorn, D. J. Ganz, and K. Hayhoe. 2012. Climate change and disruptions to global fire activity. Ecosphere **3**: 1–22. DOI: 10.1890/ES11-00345.1.

Natcher, D. C. 2004. Implications of fire policy on native land use in the Yukon Flats, Alaska. Human Ecology **32**: 421–441.

Natcher, D. C., M. Calef, O. Huntington, S. Trainor, H. P. Huntington, L. DeWilde, S. Rupp, F. S. Chapin. 2007. Factors contributing to the cultural and spatial variability of landscape burning by native peoples of interior Alaska. Ecology and Society **12**: 1–13. ISBN: 1708-3087

Nelson, J. L., E. S. Zavaleta, and F. S. Chapin. 2008. Boreal fire effects on subsistence resources in Alaska and adjacent Canada. Ecosystems **11**: 156–171.

Norris, C. E., S. A. Quideau, J. S. Bhatti, and R. E. Wasylishen. 2011. Soil carbon stabilization in jack pine stands along the Boreal Forest Transect Case Study. Global Change Biology **17**: 480–494.

North, M. P., and M. D. Hurteau. 2011. High-severity wildfire effects on carbon stocks and emissions in fuels treated and untreated forest. Forest Ecology and Management **261**: 1115–1120.

O'Donnell, J. A., J. W. Harden, A. D. Mcguire, M. Z. Kanevskiy, M. T. Jorgenson, and X. Xu. 2011. The effect of fire and permafrost interactions on soil carbon accumulation in an upland black spruce ecosystem of interior Alaska: Implications for post-thaw carbon loss. Global Change Biology **17**: 1461–1474.

O'Donnell, J. A., M. R. Turetsky, J. W. Harden, K. L. Manies, L. E. Pruett, G. Shetler, and J. C. Neff. 2009. Interactive effects of fire, soil climate, and moss on CO_2 fluxes in black spruce ecosystems of interior Alaska. Ecosystems **12**: 57–72.

Ping, C.-L., G. J. Michaelson, M. T. Jorgenson, J. M. Kimble, H. Epstein, V. E. Romanovsky, and D. A. Walker. 2008. High stocks of soil organic carbon in the North American Arctic region. Nature Geoscience **1**: 615–619.

Prentice, I. C., and S. P. Harrison. 2009. Ecosystem effects of CO_2 concentration: evidence from past climates. Climate of the Past Discussions **5**: 937–963.

Prentice, I. C., D. I. Kelley, P. N. Foster, P. Friedlingstein, S. P. Harrison, and P. J. Bartlein. 2011. Modeling fire and the terrestrial carbon balance. Global Biogeochemical Cycles **25**: 1–13. DOI: 10.1029/2010GB003906.

Randerson, J. T., H. Liu, M. G. Flanner, S. D. Chambers, Y. Jin, P. G. Hess, G. Pfister, M. C. Mack, K. K. Treseder, L. R. Welp, F. S. Chapin, J. W. Harden, M. L. Goulden, E. Lyons, J. C. Neff, E. a G. Schuur, C. S. Zender. 2006. The impact of boreal forest fire on climate warming. Science **314**: 1130–1132.

Root, T., J. Price, K. Hall, S. Schneider. 2003. Fingerprints of global warming on wild animals and plants. Nature **421**: 57–60.

Routh, J., G. Hugelius, P. Kuhry, T. Filley, P. K. Tillman, M. Becher, and P. Crill. 2014. Multi-proxy study of soil organic matter dynamics in permafrost peat deposits reveal vulnerability to climate change in the European Russian Arctic. Chemical Geology **368**: 104–117.

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

Shaver G. R., F. S. Chapin III. 1991. Biomass Relationships and Element Cycling in Contrasting Arctic Vegetation Types. Ecological Monographs **61**: 1–31.

Shenoy, A., J. F. Johnstone, E. S. Kasischke, and K. Kielland. 2011. Persistent effects of fire severity on early successional forests in interior Alaska. Forest Ecology and Management **261**: 381–390.

Smith, R. J., J. C. Benavides, S. Jovan, M. Amacher, and B. McCune. 2015. A rapid method for landscape assessment of carbon storage and ecosystem function in moss and lichen ground layers. The Bryologist **118**:32–45.

Soja, A. J., N. M. Tchebakova, N. H. F. French, M. D. Flannigan, H. H. Shugart, B. J. Stocks, A. I. Sukhinin, E. I. Parfenova, F. S. Chapin, and P. W. Stackhouse. 2007. Climate-induced boreal forest change: Predictions versus current observations. Global and Planetary Change **56**: 274–296.

State of Alaska, United States Department of The Interior, United States Department of Agriculture. 2016. Alaska interagency wildland fire management plan. State of Alaska Emergncy Response Commission (SERC). Anchorage, AK. 99501. http://fire.ak.blm.gov/.

Stavros, E. N., J. Abatzoglou, N. K. Larkin, D. Mckenzie, and E. A. Steel. 2014. Climate and very large wildland fires in the contiguous western USA. International Journal of Wildland Fire **23**: 899–914.

Tamocai, C., J. G. Canadell, E. A. G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov. 2009. Soil organic carbon pools in the northern circumpolar permafrost region. Global Biogeochemical Cycles **23**: 1–11. DOI: 10.1029/2008GB003327.

Tan, Z., L. L. Tieszen, Z. Zhu, S. Liu, and S. M. Howard. 2007. An estimate of carbon emissions from 2004 wildfires across Alaskan Yukon River Basin. Carbon balance and management **2**: 1–8. DOI: 10.1186/1750-0680-2-12.

Tape, K. D., D. D. Gustine, R. W. Ruess, L. G. Adams, and J. A. Clark. 2016. Range expansion of moose in Arctic Alaska linked to warming and increased shrub habitat. PLoS ONE **11**:1–13. DOI: 10.1371/journal.pone.0160049

Taş, N., E. Prestat, J. W. McFarland, K. P. Wickland, R. Knight, A. A. Berhe, T. Jorgenson, M. P. Waldrop, and J. K. Jansson. 2014. Impact of fire on active layer and permafrost microbial communities and metagenomes in an upland Alaskan boreal forest. ISME Journal **8**: 1904–1919.

Turetsky, M. R., E. S. Kane, J. W. Harden, R. D. Ottmar, K. L. Manies, E. Hoy, E. S. Kasischke. 2014. Recent acceleration of biomass burning and carbon losses in Alaska forests and peatlands. Ecological Applications **22**: 1–11. DOI: 10.1111/jvs.12443.

Wang, G. G., and K. J. Kemball. 2010. Effects of fire severity on early survival and growth of planted jack pine, black spruce and white spruce. Forestry Chronicle **86**: 193–199.

Wendler, G., and S. Martha. 2009. A century of climate change for Fairbanks, Alaska. Arctic **62**: 295–300.

Yi, S., A. D. McGuire, E. Kasischke, J. Harden, K. Manies, M. MacK, and M. Turetsky. 2010. A dynamic organic soil biogeochemical model for simulating the effects of wildfire on soil environmental conditions and carbon dynamics of black spruce forests. Journal of Geophysical Research: Biogeosciences **115**: 1–15. DOI: 10.1029/2010JG001302.

Young, A. M., P. E. Higuera, P. A. Duffy, and F. S. Hu. 2016. Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. Ecography **39**: 1–12. DOI: 10.1111/ecog.02205.

Young, B., J. Yarie, D. Verbyla, F. Huettmann, K. Herrick, and F. S. Chapin. 2016. Modeling and mapping forest diversity in the boreal forest of interior Alaska. Landscape Ecology **39**: 1–17. DOI: 10.1007/s10980-016-0450-2.

GIS Data Resources/ References Cited:

Alaska Climate Research Center. Temperature Changes in Alaska. Accessed on web. 03 Mar. 2017. <http://climate.gi.alaska.edu/ClimTrends/Change/TempChange.html>.

Allen, D. 2010. GIS 2: Spatial Analysis Workbook, 3rd Edition. ArcGIS 10.1. Third Edit. ESRI Press, 380 New York Street, Redlands, CA. 92373, Redlands, CA.

Hugelius, G., C. Tarnocai, G. Broll, J. G. Canadell, P. Kuhry, and D. K. Swanson. 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 **5**: 3–13.

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

Jorgenson, T., K. Yoshikawa, M. Kanevskiy, Y. Shur, V. Romanovsky, S. Marchenko, and G. Grosse. 2008. Permafrost characteristics of Alaska. Page Institute of Northern Engineering, University of Alaska- Fairbanks. Fairbanks, AK 99704.

Mitchell, A. 2009. The ESRI Guide to GIS Analysis Volume 2: Spatial Measurments & Statistics. First Edit. ESRI Press, 380 New York Street, Redlands, CA. 92373

Nowacki, G., S. Page, M. Fleming, B. Terry, T. Jorgenson. Ecoregions of Alaska: 2001. U.S. Geological Survey Open-File Report 02-297. Accessed 10/29/2016. http://www.fs.fed..us/rm/ecoregions/products/map-ecoregions-north-america/#

National Oceanic Atmospheric Administration. 2011. Wildfires - Annual 2011. State of the Climate National Centers for Environmental Information (NCEI). Web. 11 March 2017.

National Oceanic Atmospheric Administration. 2010. Wildfires- 2010 annual. State of the Climate National Centers for Environmental Information (NCEI). Web. 11 March 2017.

Olefeldt, D., S. Goswami, G. Grosse, D.J. Hayes, G. Hugelius, P. Kuhry, B. Sannel, E.A.G. Schuur, and M.R. Turetsky. 2016. Arctic Circumpolar Distribution and Soil Carbon of Thermokarst Landscapes, 2015. ORNL DAAC, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1332

Shute, J. 2015. Alaska Fire History 1940-Present. Created from data found at http://afsmaps.blm.gov/imf/imf.jsp?site=firehistory. Accessed 12/1/2016, www.ESRIonline.com.

USDA, USFS, USGS, RSAC. 2016. Monitoring Trends in Burn Severity. Created from data found at http://www.mtbs.gov/index.html. Accessed 2/17/2017.

USDA Forest Service Forest Inventory and Analysis Program and Remote Sensing Applications Center. 2011. Digital representation Atlas of United States Trees. http://app.databasin.org/app/pages/datasetPage.jsp?id=8766b533770d4e30b431f880a6a8b0f7 and http://esp.cr.usgs.gov/data/atlas/little/. Accessed 12/15/2016.

Appendix A:

Supporting Figures & Tables (from Literature)

Figures in this section are useful for understanding processes or trends outlined in Section 3.0 Evidence, but were not essential for providing evidentiary proof of the effects that wildfire has on carbon cycles due to permafrost retreat, climate change, or spatially diverse soil carbon volumes.

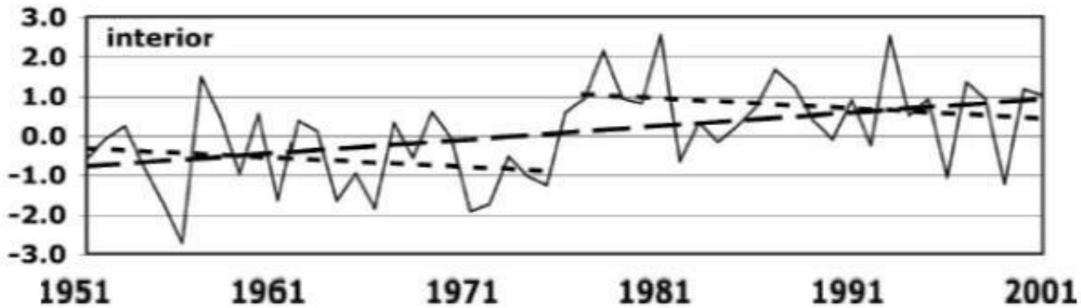


Figure 1 Appendix A: Time series of the mean annual departure from average temperature in degrees C of the Interior Alaska climate region from 1951 to 2001. The least squares linear regression lines for 1951– 2001, 1951–75, and 1977–2001 are included (Image and caption from Hartman & Wendler 2005).

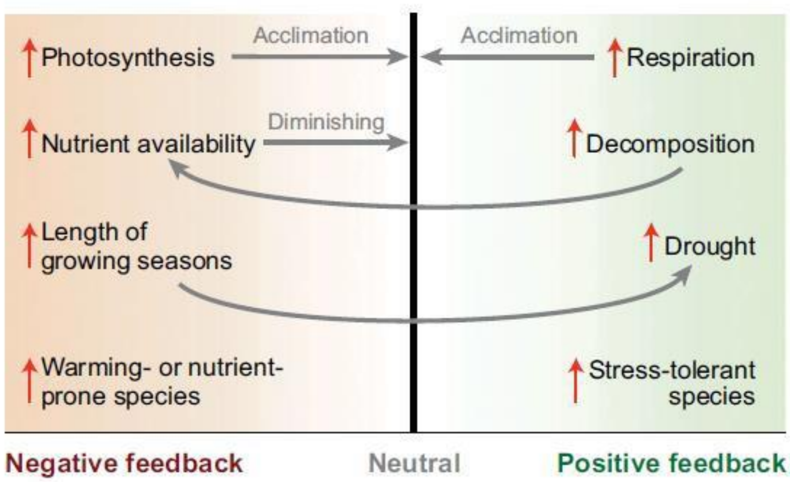


Figure 2 Appendix A: Schematic summary of major regulatory mechanisms that lead to either positive or negative feedbacks of terrestrial C cycles to climate warming. Image from Luo 2007.

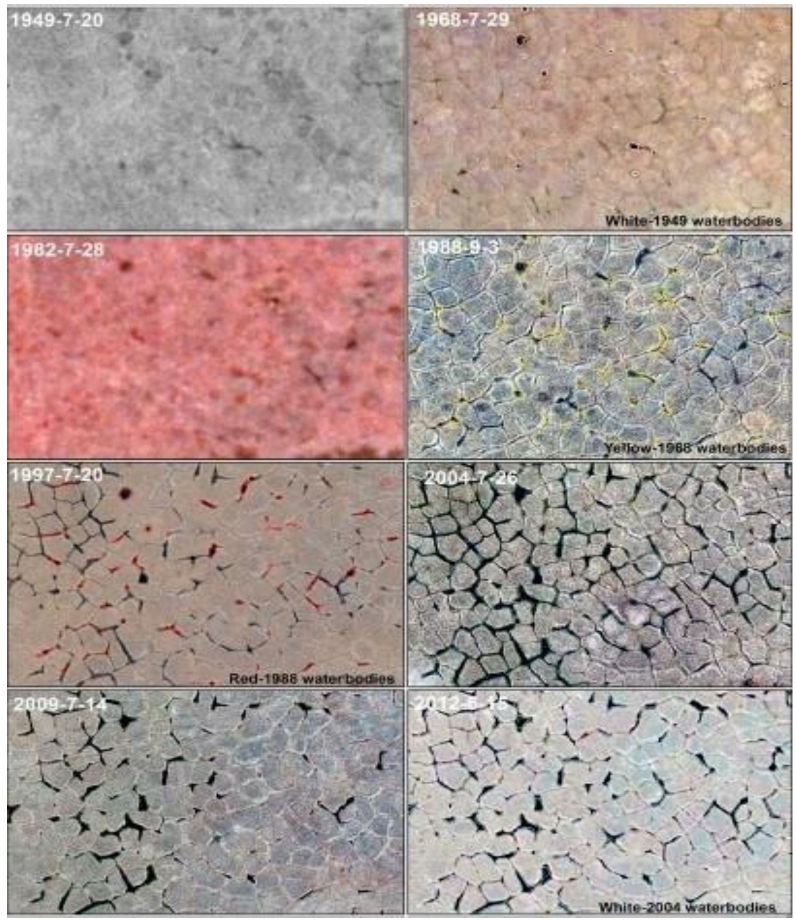


Figure 3 Appendix A: Changes in waterbody distribution associated with thermokarst troughs and low-centered polygons from 1949 to 2012 at Prudhoe Bay, Alaska. Waterbodies from previous years are overlaid on air photos. Image and caption from Jorgenson et. al. 2015.

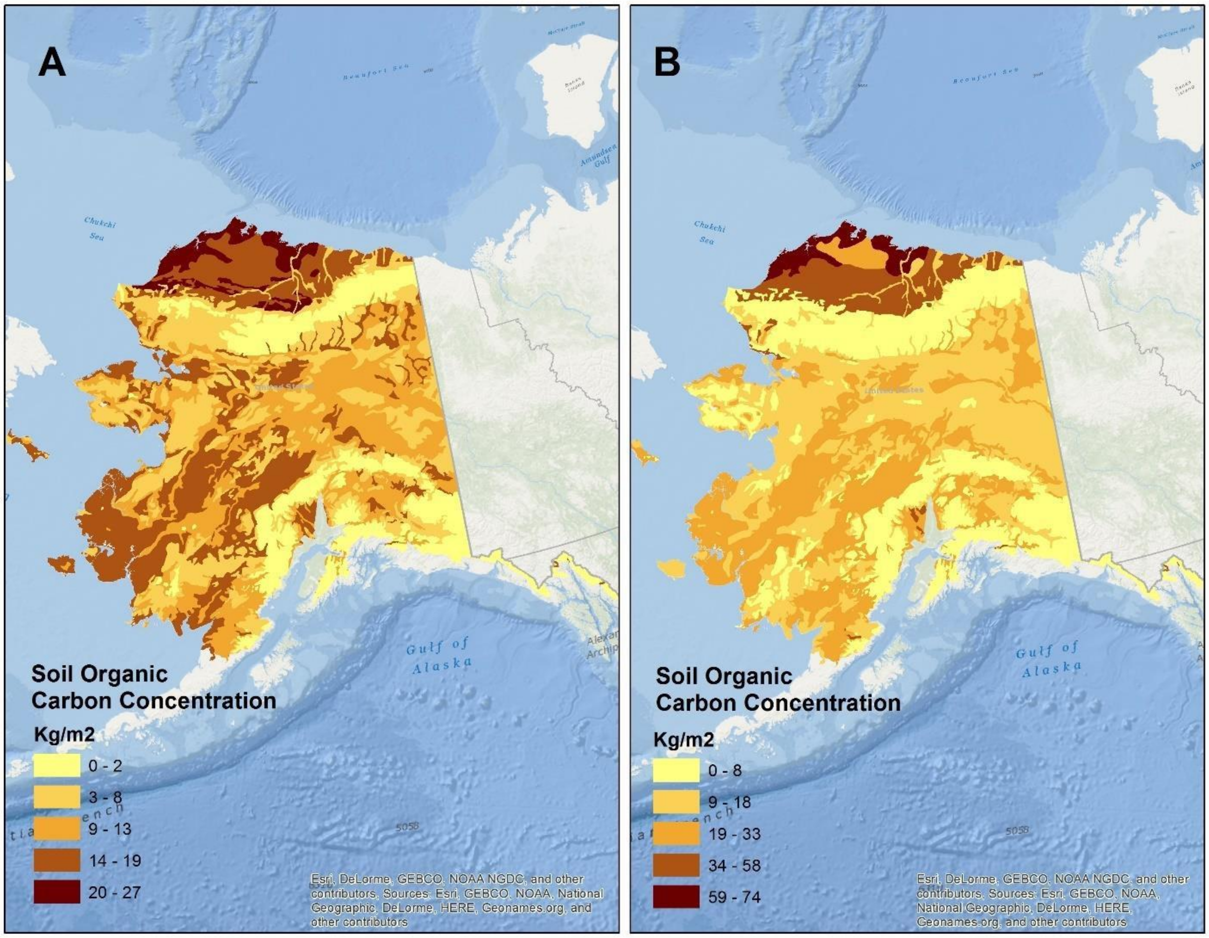


Figure 4 Appendix A: Soil organic carbon content in Kg/m^2 throughout the State of Alaska at 30 cm depth (A) and 100 cm depth (B) (data source: NCSCD, Hugelius et. al. 2013).

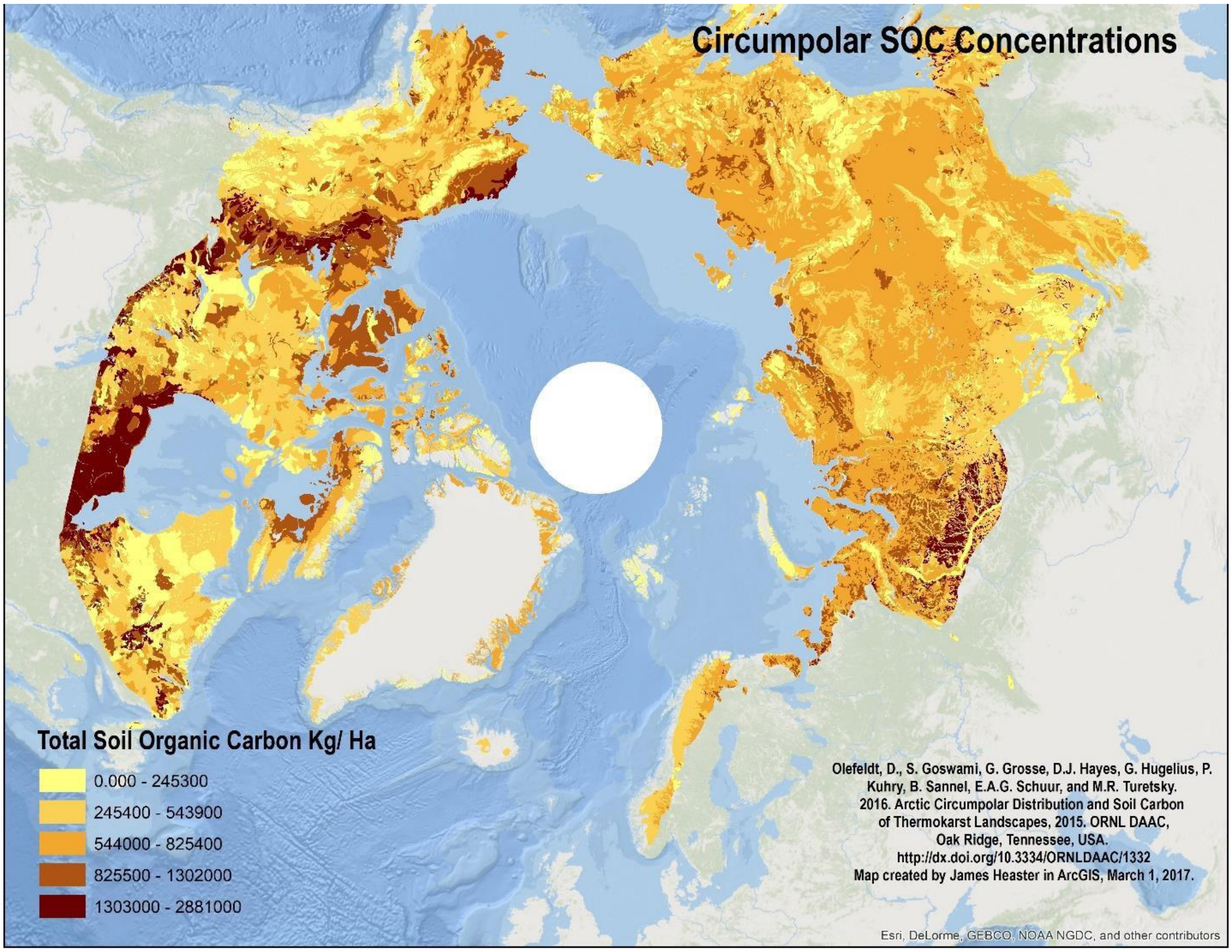


Figure 5 Appendix A: The total soil organic carbon concentration for global circumpolar regions in Kg per hectare. Data from Olefeldt et. al. 2016 and Hugelius et. al. 2013. Map created by James Heaster with ArcGIS® software.

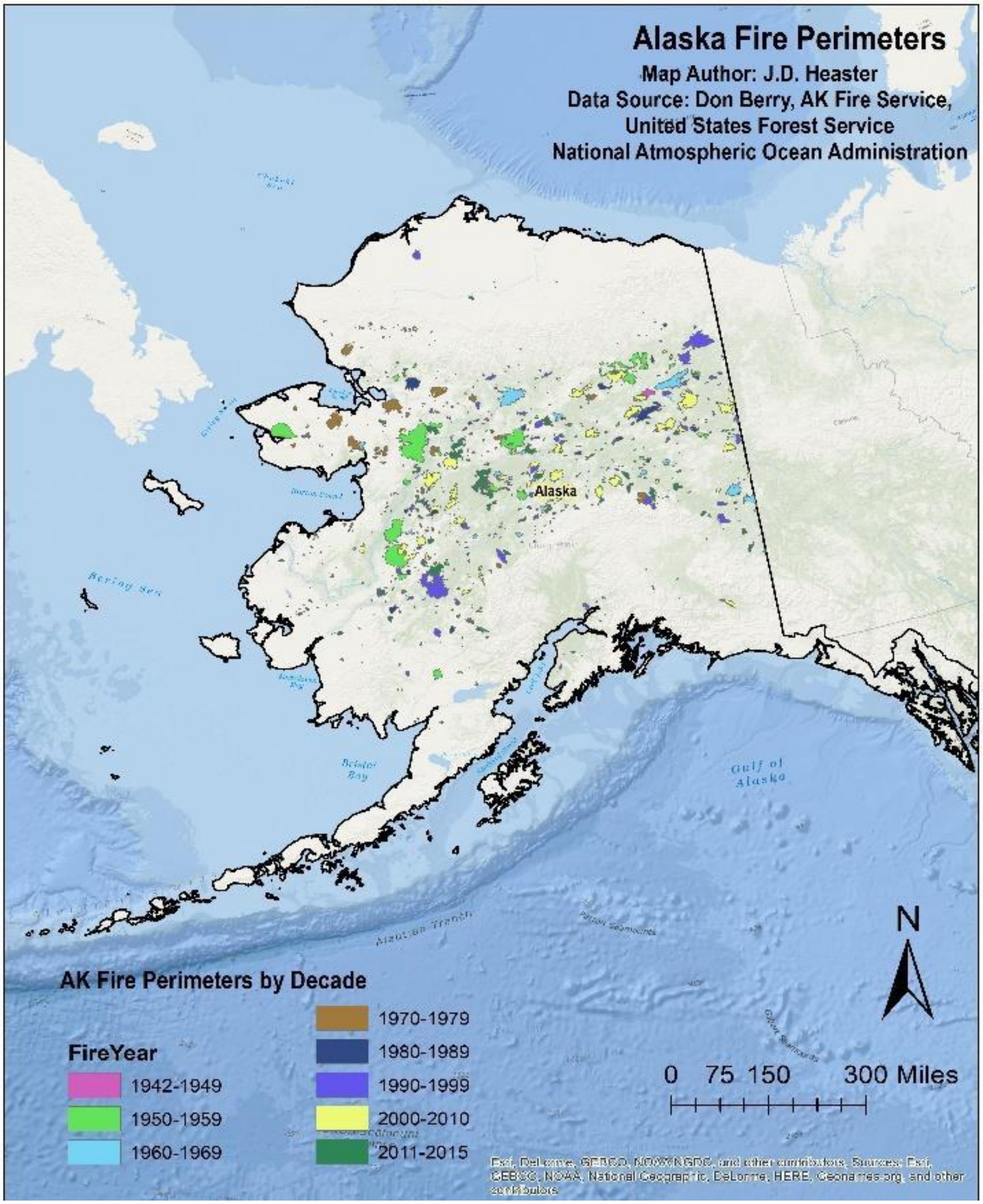


Figure 6 Appendix A: Wildfire polygons for the State of Alaska from 1942- until present. These data were assembled from the USGS and the Alaska Fire Service and digitized using ArcGIS® software by James Heaster.

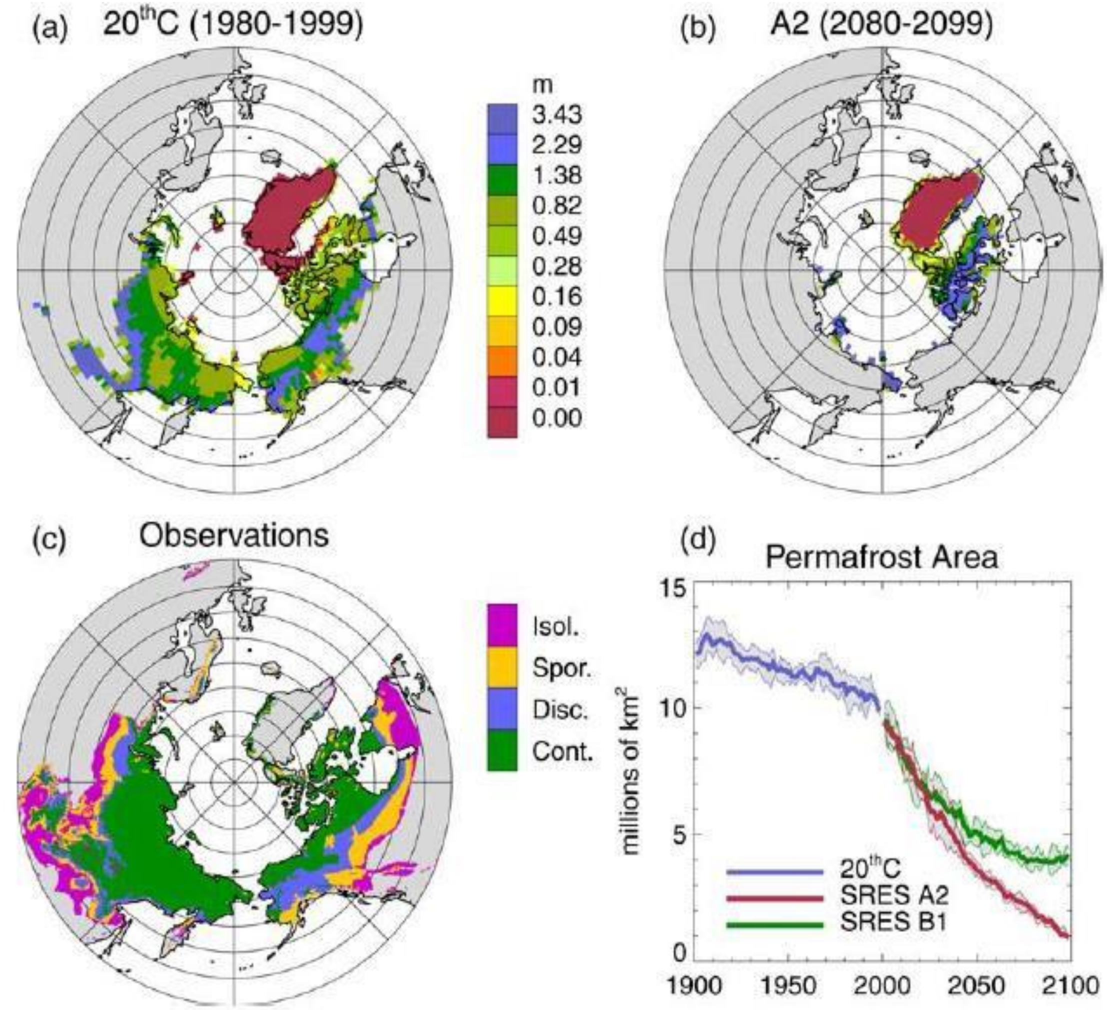


Figure 7 Appendix A: Ensemble mean permafrost area and active layer thickness as simulated in CCSM3 at the end of the (a) 20th and (b) 21st centuries. (c) Observational estimates of permafrost (continuous, discontinuous, sporadic, and isolated). (d) Time series of simulated global permafrost area (excluding glacial Greenland and Antarctica). The gray shaded area represents the ensemble spread. Image and caption from Lawrence and Slater 2005.

Table 1 Appendix A: Permafrost extents by total area and concentration of carbon per hectare in Megagrams. Note that although isolated permafrost extents are the third smallest extent in the region, it holds the most soil organic carbon in mega grams per hectare. Data compiled from Jorgensen et. al. 2013 the NCSCD, Hugelius et. al. 2013, and processed with ArcGIS® software.

Permafrost Code	Code	Area (Hectares)	Mg TSOC/HA
C	Continuous	2,902,982	702.6
D	Discontinuous	6,267,747	580.3
I	Isolated	283,421	1095.0
S	Sporadic	838,738	518.4
U	Absent	52,864	625.2
W	Large Waterbodies (unfrozen)	8,426	475.4

Table 2 Appendix A: Fire perimeters by permafrost extent and SOC losses in the boreal region. Fire data obtained from the Alaska Fire Service and the SOC data are from the NCSCD (Hugelius et. al. 2013).

Fire Year	MONTH	PFE	Fire Area (Ha)	MgC/ Ha	Total Carbon Loss
2000	11	D	27,147	2,902	78,772,402
2000	11	I	11,180	2,190	24,483,619
2000	11	S	28,454	1,037	29,503,204
2002	7	D	493	580	285,984
2002	8	D	9,321	2,902	27,045,348
2002	9	D	29,256	3,482	101,869,761
2002	9	S	5,218	518	2,705,449
2002	11	D	7,297	1,741	12,704,100
2003	6	C	3,335	703	2,343,572
2003	6	D	39,530	2,902	114,705,141
2004	4	D	4,595	580	2,666,538
2004	6	D	2,113	1,161	2,452,476
2004	7	C	108	703	75,874
2004	7	S	4	518	1,853
2004	8	C	1	703	1,043
2004	8	D	2,495	1,161	2,895,737
2004	9	C	36,916	2,108	77,813,041
2004	9	D	611	1,161	708,883
2004	11	D	32,014	580	18,579,287
2004	11	I	2,295	5,475	12,567,005
2004	12	D	7,959	580	4,618,970
2004	12	S	350	518	181,399
2005	8	D	61,549	4,643	285,754,825
2005	11	D	57,004	1,741	99,245,122
2007	5	D	189	2,321	437,757
2007	6	C	1,656	2,108	3,489,992
2007	6	D	12	580	7,109

2007	7	C	164	1,405	230,226
2007	7	D	2,692	2,902	7,812,017
2007	8	C	2,105	703	1,479,122
2008	5	D	212	2,321	491,417
2008	7	C	4	703	2,656
2008	7	D	231	1,741	402,159
2009	6	I	129	1,095	140,949
2009	7	D	3,017	580	1,750,940
2009	7	S	8,100	518	4,199,393
2009	8	D	47,349	6,964	329,745,885
2009	9	D	11,241	580	6,523,380
2010	5	D	281	580	163,228
2010	6	C	56	2,810	158,396
2010	6	D	8,659	9,285	80,401,744
2010	7	C	1,064	1,405	1,495,196
2010	7	D	12,405	2,321	28,795,913
2010	10	C	8,079	4,216	34,059,850
2010	10	D	1,238	580	718,389
2011	6	D	20,901	1,161	24,258,834
2011	7	C	71	703	49,581
2011	7	D	4	580	2,521
2011	8	C	0	703	8
2012	6	C	1,168	2,108	2,462,339
2012	6	D	62	580	35,980
2012	7	C	2,166	2,108	4,565,990
2012	7	D	3,697	1,161	4,291,453
2012	9	D	113	580	65,798
2012	10	D	32	580	18,428
2013	6	D	161	580	93,452
2013	6	S	890	518	461,382
2013	7	D	5	580	2,883
2013	8	D	24,527	4,062	99,636,119
2013	8	S	473	518	245,095
2013	10	D	0	580	66
2014	4	D	184	1,161	213,222
2014	5	I	3,566	5,475	19,525,204
2015	5	D	512	3,482	1,783,009
2015	6	D	1,673	1,741	2,913,105
2015	7	D	11,439	6,964	79,663,107
2015	7	I	278	2,190	608,180
2015	7	S	1,080	1,555	1,679,890
2015	8	D	21,686	4,643	100,680,216
2015	8	I	7	1,095	7,409
2015	9	C	2,779	1,405	3,904,805
2015	9	D	90,425	4,062	367,341,322

Table 3 Appendix A: Soil type by area and mass carbon by each soil taxa.: Soil types by area within the boreal region of central Alaska and associated soil organic carbon mass in kilograms. Although miscellaneous soil types comprise a small regional there was no organic carbon data recorded for these areas within the NCSCD (Hugelius et. al. 2013). These areas generally correspond with areas of bare rock or similar geologic formations, or wetland areas such as collapse scar bogs or water logged soils (data from the NCSCD, Hugelius et. al. 2013).

Soil Type	Area (Ha)	SOC Mass @ 30 cm (Kg)	SOC Mass @100 cm (Kg)
Gelisol	46,944,567	4,300,339,935,486	6,059,157,778,016
Entisol	46,944,567	282,887,747,776	577,091,005,462
Inceptisol	12,300,945	664,251,080,437	1,168,589,863,731
Spodosol	3,239,516	317,472,614,115	589,591,997,642
Aquatic	1,659,036	228,947,096,147	371,624,272,006
Mollisol	230,798	20,771,829,559	31,619,340,551
Histosol	5,284	956,472,056	3,318,588,128
Andisol	174,822	19,929,719,400	44,404,813,400
Turbel	28,527,902	3,872,953,504,378	4,907,030,085,540
Orthel	306	28,125,924	66,034,777
Histel	3,823,227	427,358,305,184	1,152,061,657,698
Miscellaneous	248,125	ND	ND