ABSTRACT

Title of Dissertation: Impacts of a changing fire frequency on soil carbon stocks in interior Alaskan boreal forests.

Elizabeth Embury Hoy, Doctor of Philosophy, 2014

Directed By: Professor Eric S. Kasischke, Department of Geographical Sciences

Increasing temperatures and drier conditions, related to climate change, have resulted in changes to the fire regime in interior Alaskan boreal forests, including increases in burned area and fire frequency. These fire regime changes alter carbon storage and emissions, especially in the thick organic soils of black spruce (*Picea mariana*) forests. While there are ongoing studies of the size and severity of fire using ground- and remote-based studies in mature black spruce forests, a better understanding of fire regime changes to immature black spruce forests is needed. The goal of this dissertation research was to assess impacts of changing fire frequency on soil organic layer (SOL) carbon consumption during wildland fires in recovering Alaskan black spruce forests using a combination of geospatial and remote sensing analyses, field-based research, and modeling. The research objectives were to 1) quantify burning in recovering vegetated areas; 2) analyze factors associated with variations in fire frequency; 3) quantify how fire frequency affects depth of burning, residual SOL depth, and carbon loss in the SOL of black spruce forests; and 4) analyze how fire frequency impacts carbon consumption in these forests. Results showed that considerable burning in the region occurs in stands not yet fully recovered from earlier fire events (~20% of burned areas are in immature stands). Additionally, burning in recovering black spruce forests (~40 yrs old) resulted in SOL depth of burn similar to that in mature forests which have burned. Incorporating these results into a modeling framework (through adding an immature black spruce fuel type and associated ground-layer carbon consumption values) resulted in higher ground-layer carbon consumption (and thus total carbon consumed) for areas that burned in 2004 and 2005 than that of a previous version of the model. This research indicated that the dominant controls on fire behavior in this system were fuel type and amount, not fuel condition, and that changes in vegetation associated with more frequent fire (shift to deciduous and shrub vegetation which does not traditionally burn as readily) may represent a long-term negative feedback on burned area. These new results provide insight into the fire-climate-vegetation dynamics within the region and could be used to both inform and validate modeling efforts to better estimate soil carbon pools and emissions as climate continues to change.

IMPACTS OF A CHANGING FIRE FREQUENCY ON SOIL CARBON STOCKS IN INTERIOR ALASKAN BOREAL FORESTS.

By

Elizabeth Embury Hoy

Dissertation submitted to the Faculty of the Graduate School of the
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Advisory Committee:
Professor Eric S. Kasischke, Chair
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Dedication

To my family – all of them – for their overwhelming encouragement and support throughout this process.

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I am indeed thankful for many who have assisted me on this journey. I have learned so much about myself, but also about the amazing support structure that a family can provide. Without their steadfast support and encouragement, as well as substantial childcare, this dissertation would not have been possible. I am grateful for the guidance of my advisor, Professor Eric S. Kasischke; his insight has helped me to think critically and ask the in-depth questions needed to turn an idea into a body of research. The encouragement and support of Assistant Professor Tatiana V. Loboda has also been instrumental in the completion of this research. I would also like to thank the other members of my committee for their advice and suggestions – Professors Samuel N. Goward, Stephen D. Prince and Joseph H. Sullivan.

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Chapter 1: Introduction

1.1 Overview

The U.S. Climate Change Science Program (CCSP) estimates that North America is currently a net carbon source of approximately 1,336 ± 334 Mt C yr^{-1} (SOCCR 2007). Modeling work has shown that northern latitude systems could lose up to 50 Gt C over the next 100 years, and it has been shown that carbon storage in these systems is vulnerable to changes in climate and fire disturbance (CCSP 2009). The largest carbon sink present in North America is in forests (SOCCR 2007) and the boreal forest biome is one of the largest terrestrial carbon stores across North America, mainly due to the large carbon pool stored in the soils of peatlands and forests of the boreal region (Kasischke et al. 1995). Climate change is likely leading to changes in the processes controlling formation of these soils, especially the surface organic layer, becoming more vulnerable to increased consumption during fires (Turetsky et al. 2011b), making further research and scientific understanding in this region crucial.

Much of the carbon stored in North American boreal forests is in the deep organic soils of black spruce (*Picea mariana*) forests. In interior Alaska alone, black spruce forests represent 66% of all forested land and the deep organic soil layers located here store 865 ± 104 Tg C (Turetsky et al. 2011b). Recent studies have shown that an average of greater than 30 t C ha^{-1} is released from the burning of surface organic matter in Alaskan black spruce forests (Turetsky et al. 2011b), which is ten times the amount released from the burning of above-ground biomass in this ecosystem (Kasischke and Hoy 2012). Despite the considerable research in the boreal forest regions of Alaska and Canada, gaps in understanding ecosystem processes still remain. Changes in fire frequency are resulting in the burning of immature forests, and the effects of such burning are still unknown. More detailed spatial information is needed to reduce uncertainty in carbon consumption estimates due to wildfire (French et al. 2004), including information on the amount of burning in the soil organic layer (Kasischke et al. 2005), especially in relation to burning in forests recovering from recent fire (0-60 year old stands).

1.2 Research Objectives

One important characteristic of the fire regime in the boreal forest is the frequency of fire, characterized through different metrics such as the average time needed to burn a region of a given size (fire return interval or its inverse, fire frequency) or the time of last burn between specific fire events at a local scale (fire-free interval). There are ongoing studies of the size and severity of fire using ground and remote-based studies in mature black spruce forests; however a better understanding of fire regime changes in immature black spruce forests is still needed. Detailed research related to changing fire frequency and its effects on soil carbon stocks in interior Alaska, using a combination of geospatial/remote sensing, field-based and modeling efforts, has the potential to improve the understanding of carbon cycling in relation to wildland fire in this region.

The overarching goal of this dissertation research is to investigate how an increase in fire frequency and a decrease in fire-free interval (FFI) influence soil organic layer carbon consumption during wildland fires. To address this goal two hypotheses were developed:

Hypothesis 1: As fire frequency increases, the fraction of area burned within a fire perimeter decreases.

Hypothesis 2: As fire-free interval decreases, the fractional depth of burning increases.

In order to test these hypotheses, assessments of fire regime factors associated with soil carbon stocks in Alaskan boreal forests were made to address four objectives (Figure 1-1):

1. Determine the fraction of the landscape burned in order to analyze fire frequency and other fire regime characteristics across the interior boreal region of Alaska using satellite remote sensing data products;

2. Using this information product, analyze factors that are associated with variations in fraction of burned area across the landscape (topography and vegetation) and fire occurrence (fire frequency, seasonality of burning and yearly burned area);

3. Through field studies, quantify how fire frequency affects the depth of burning, the residual organic layer depth, and carbon loss in the soil organic layer in the black spruce forests of Alaska; and

4. Through the use of a modeling framework, analyze how fire frequency impacts carbon consumption in Alaskan black spruce forests.

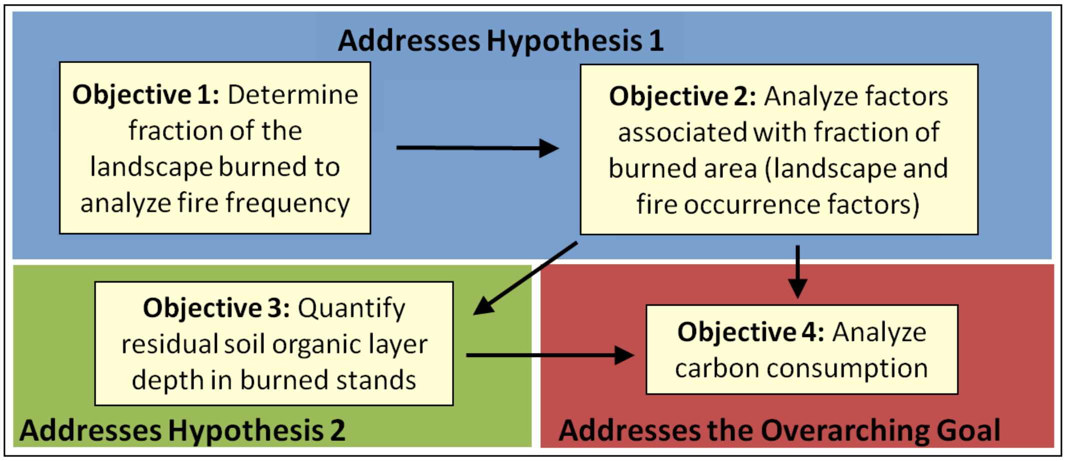

Figure 1-1: Flow diagram indicating the objectives created to answer the hypotheses and overarching goal.

1.3 Background

Numerous changes have been observed in the fire regime of the North American boreal forest (Gillett et al. 2004, Kasischke and Turetsky 2006, Kasischke et al. 2010), and climate change (including increasing temperatures and decreased rainfall) has been cited as a possible control (Duffy et al. 2005, Skinner et al. 2006). Recent research in the boreal forests of Canada has shown that at the same time as the summer season temperatures have warmed over the past four decades, area burned by forest fires has also increased (Gillett et al. 2004). This change in area burned is due primarily to increases in the frequency of large fire years and late season burning (Kasischke and Turetsky 2006, Kasischke et al. 2010, Turetsky et al. 2011b) during the same time frame. In the last 30 years alone, annual surface temperatures in boreal regions have increased by 3 – 5°C (Chapin et al. 2000), and recent warming is likely to continue into the future. Projections of future climate change in Alaska by both the Canadian Climate Center (CGCM1) and the Hadley Centre (HADCM2SUL) indicate a temperature rise of between 5 and 8°C by the end of the 21st century (Bachelet et al. 2005). Additional research in the Canadian boreal forest, which is based on an analysis of historical weather patterns and area burned calculations, has shown that area burned could increase by 74 – 118% by the end of the 21st century assuming a tripling of CO_2 in the region (Flannigan et al. 2005).

The research for this dissertation focused on the interior Alaskan boreal region (Figure 1-2), which covers over 46.9×10^6 ha and contains nine ecoregions which represent areas of similar ecological conditions (Nowacki et al. 2001). In this intermontane boreal region, the continental climate is dominated by long severe winters and short summers where the growing season can be less than 135 days (from early May to mid-September). Temperatures can range from -50°C in January to +33°C in July, while precipitation can range from 170 mm to 550 mm per year (Hinzman et al. 2006). The cold winter temperatures and short growing season found here have resulted in slow decomposition rates in the soil organic layer and thus thick organic soils (Ping et al. 2006). Many of the forest fires in Alaska occur in the interior boreal region of Alaska, likely due to the hot and dry summers, as well as the thick organic soils and extensive tree cover (Figure 1-2b) in this region (Kasischke et al. 2002). The current fire return intervals (FRI) in the interior Alaskan boreal region can range from <120 years to >360 years based on the specific ecoregion and elevation, although these estimates have begun to change based on the inclusion of burned areas from 2000-2009 (Kasischke et al. 2002, Kasischke et al. 2010).

Studies analyzing aspects of the fire regime in this interior Alaskan boreal forest region include assessments of the fire frequency (Balshi et al. 2007, Kasischke et al. 2010), landscape patterns of burned area (Turetsky et al. 2011b), carbon storage (Kasischke et al. 1995, Harden et al. 2000) and the influence of climate (Duffy et al. 2005, Balshi et al. 2009b, Flannigan et al. 2009). Some recent analyses have assessed not only individual aspects of the boreal ecosystem, but have considered the overarching climate-fire-vegetation dynamics within this region (Johnstone et al. 2011, Mann et al. 2012, Kelly et al. 2013), and how these dynamics will influence the future composition of Alaskan boreal forests. Additionally, since black spruce forests dominate the ecosystem of interior Alaska, considerable research has been done in these forests. Field research in mature black spruce forests has documented relationships between topography, fire seasonality, fire size, and depth of burn in these forests, such as differences in depth of burn on north and south facing slopes or differences between early and late season burning (Kane et al. 2007, Turetsky et al. 2011b). Factors controlling changes in the successional trajectories of boreal forests following fire have been addressed as well (Johnstone et al. 2010b, Johnstone et al. 2011). Others have begun to examine the effects of fire in younger, immature black spruce forests (Brown and Johnstone 2011, Brown and Johnstone 2012), although this research occurred in the boreal forests of Canada. The research in this dissertation will help to address issues related to burned area and the fire regime in immature, recovering areas within the boreal forests of Alaska.

1.4 Dissertation Organization

This dissertation is organized into 5 chapters. Chapters 1 and 5 provide the introduction and conclusion to the dissertation, respectively, while Chapters 2 to 4 present the research carried out for this dissertation. To be consistent, Chapters 2 to 4 are presented in a stand-alone format used for journal articles. These research oriented chapters are organized to correspond with the four objectives, two hypotheses and the overarching goal (Figure 1-1).

Chapter 2 discusses the creation of the burned area product used to analyze fire frequency, based on combining several geospatial and remote sensing datasets. The various factors believed to be connected to both fire frequency and the fraction of burned area within a fire event perimeter are analyzed using the fire frequency geospatial dataset. This research addresses Hypothesis 1. This chapter is currently under review by *Environmental Research Letters*.

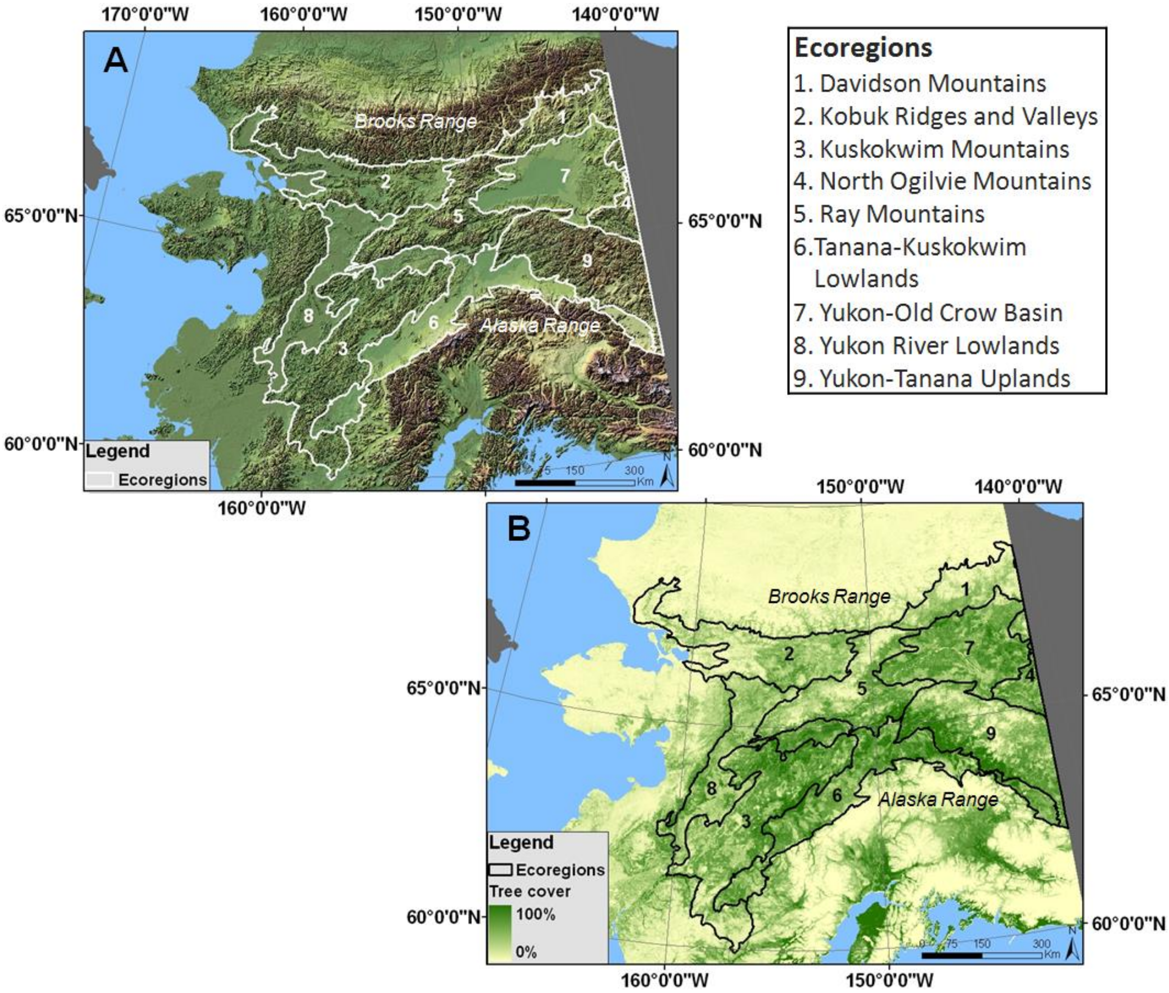

Figure 1-2: Topography and tree cover in Alaska. A) Elevation of Alaska; range from 0 ft (light green) to >6500 ft (brown). B) Tree cover. Both (A) and (B) show the outline of the nine ecoregions contained with the interior boreal forest region of Alaska, located between the Brooks Range to the North and the Alaska Range to the South.

Chapter 3 uses the fire frequency burned area geospatial data product developed in Chapter 2 as a guide for field research in interior Alaskan boreal forests which had experienced fire at least twice in the last 60 years. This research assessed depth of burn within the soil organic layers of immature black spruce forests, thus meeting Objective 3 and investigating Hypothesis 2. This chapter is currently under review by the *International Journal of Wildland Fire*.

Chapter 4, using results from Objectives 1 through 3, meets Objective 4 and addresses the Overarching Goal. In this chapter, the impact of fire frequency on soil carbon stocks within the boreal forests of Alaska is investigated. This chapter is currently under review by the *Journal of Geophysical Research - Biogeosciences*.

As noted above, Chapter 5 presents the overall conclusions of this doctoral research. Also in this chapter are potential future research topics and policy implications resulting from the research.

Chapter 2: Fire occurrence associations with fire frequency in Alaskan boreal forests[1]

2.1 Introduction

The interior region of Alaska contains large carbon stores in the thick organic soil layers found in the terrestrial ecosystems of this region. These carbon stores are becoming increasingly vulnerable to changes in temperature (Chapin et al. 2000) and fire severity (Turetsky et al. 2011b). The boreal forest region in Alaska is over 450 x 10^3 km^2 and in the past decade an area of 7.67 x 10^3 km^2 burned on average per year, in most cases ignited by lightning strikes and not by humans (Kasischke et al. 2010). This is 50% more burning than has been seen in previous decades dating back to the 1940s, when detailed record keeping began in the region (Kasischke et al. 2010). It has also been found that fire frequency is higher now than it has been since the establishment of boreal forests in this region (Kelly et al. 2013). Burning at this level has led some regions of the interior to become net sources of carbon to the atmosphere (Turetsky et al. 2011b, Yuan et al. 2012), and deeper burning is possible due to warming climate and permafrost thaw (Hinzman et al. 2005), further increasing emissions. It has been estimated that carbon stores in northern latitude systems could lose up to 50 Gt C over the next 100 years (CCSP 2009).

Past research has assessed changes in the fire regime and the impacts of these changes on the boreal forests of Alaska, both through the use of field research and modeling. Studies of the fire regime in this region include assessments of burned area

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[1] Submitted to *Environmental Research Letters* (Hoy et al. in review-a).

and fire frequency (Kasischke et al. 2010), patterns of burn severity (Barrett et al. 2011), carbon cycling (Kasischke et al. 1995, Harden et al. 2000, Turetsky et al. 2011b) and the influence of climate on inter-annual variations in burned area (Duffy et al. 2005, Balshi et al. 2009b, Flannigan et al. 2009). Research in mature black spruce (*Picea mariana*) forests has documented the relationship between topography, fire seasonality, fire size and depth of burn of the surface organic layer (Kane et al. 2007, Turetsky et al. 2011b), as well as changes in the successional trajectories of boreal forests following fire (Johnstone et al. 2010a, Johnstone et al. 2010b, Kelly et al. 2013).

Field studies of burning in immature (short-FFI, ~0-30 yr interval) stands have shown effects on carbon storage and seed availability, with burns in immature stands resulting in decreased carbon storage (Brown and Johnstone 2011) and decreased seed availability (Brown and Johnstone 2012). Improved understanding of the impacts of changes to the FFI on a broad scale throughout the boreal region, both through a better understanding of fire history and the controls on the spatial and temporal patterns of fire disturbance will allow for improved knowledge of forest succession and post-fire vegetation recovery (Johnstone et al. 2010a, Johnstone et al. 2010b) and improve fire impacts modeling on vegetation dynamics and carbon cycling (Zhuang et al. 2006, Genet et al. 2013).

Although past research has focused on multiple aspects of the fire regime, more detailed spatial information is needed to reduce uncertainty in carbon cycling (Genet et al. 2013), carbon consumption estimates due to wildfire (French et al. 2004), and the vulnerability of forests in response to changes in the fire regime

(Barrett et al. 2011, Mann et al. 2012). The relationship between fire frequency and fire behavior is one such aspect of the fire regime that needs further study. Some research has indicated that fuel type and amount are the dominant controls on patterns of burned area in western subalpine forests (Cumming 2001); however others have pointed to fuel condition (*i.e.* – weather and site moisture) as the principal driver of burned area in these systems (Bessie and Johnson 1995). A more inclusive approach, in which weather, fuel type, and forest structure are all considered, has also been presented as a way to explain controls on burned area in western subalpine regions (Agee 1997). Current research in Alaska has indicated that a shift from black spruce to deciduous vegetation reduces fire frequency (Mann et al. 2012, Kelly et al. 2013), supporting the hypothesis that vegetation type and amount are important determinants of fire frequency. Others have noted that fuel availability can act as a regulator of burned area in well-drained areas within Alaska, however site moisture can act to regulate burning in poorly-drained areas (Turetsky et al. 2011b).

One measure of fire frequency is the fire-free interval (FFI), a landscape-based metric generally considered to be the time between two unique fire events at a localized plot-level scale (Johnstone 2006). Currently, there are very few regional-scale studies of the impacts of FFI as this characteristic is difficult to assess except in these localized field studies. Estimating FFI across larger regions is difficult as not all areas within a fire perimeter actually burn (see, *e.g.* Kasischke et al. 2010) and an overestimate of burned area (and an underestimate of FFI) is possible when basing estimates on using fire perimeters alone. Remote sensing methods can be used to improve mapping of actual burned area and estimating FFI because they can be used to study large areas and remote locations characteristic of boreal forests. Field fire perimeter maps do not often capture the patchiness and heterogeneity of a burned area as effectively as satellite-based remotely sensed maps which can be used to delineate burned and unburned areas within a field fire perimeter map (Lentile et al. 2006).

In this study, we examined variables associated with patterns of burning across the landscape to better understand the influence of fire frequency on fire behavior. Using a modified version of FFI, in addition to multiple geospatial and remote sensing data layers from 167 fire events which occurred between 2002 and 2008 in the Alaskan boreal forest region, we studied how the fraction of burned area (FBA) within the fire perimeters varies as a function of FFI, vegetation type, topography, and timing of the fire events during the growing season. Through this analysis, we addressed the following questions: 1) What fraction of the burned area in the study region occurred in short- to intermediate-FFI areas, 2) Does susceptibility to burning vary as a function of fire-free interval, and 3) What factors are most important in regulating spatial patterns of burning – fuel type/amount or fuel condition?

2.2 Methods

This study was restricted to the interior boreal ecoregions of Alaska (as defined by the Unified Ecoregions of Alaska (Nowacki et al. 2001)), bordered by the Brooks Range to the North and the Alaska Range to the South. Fire events from this region ranging in size from 525 ha to 217,789 ha from 2002 through 2008 were used in this research (Table 2-1); these events represented 93% of the burned perimeter area reported by the Alaska Fire Service for the years studied. For this period, there was high variability in annual burned area (related to changes in weather throughout the growing season; see, *e.g.* Abatzoglou and Kolden (2011)) across interior Alaska with small (<.5 million ha: 2003, 2006-2008), large (0.5 to 1.0 million ha; 2002) and ultra large (>1.5 million ha: 2004, 2005) fire years (classification after Kasischke and Turetsky (2006); no very large fire years (1.0 to 1.5 million ha) were studied in this analysis).

2.2.1 Fire-Free Interval

Determining the time of the previous burn for the 2002-2008 fire events, and thus FFI, was a necessary first step to analyze the landscape trends associated with burned area and fire frequency. A database of past fire perimeter areas (from 1950 to 2001) was compared with the more detailed burned area dataset for the fire events from 2002-2008 to determine a modified form of FFI. The Alaskan Large Fire Database (LFDB) (Kasischke et al. 2002), was used to determine the year of the previous burn on the landscape from 1950 through 2001 (while the database is available from 1942 to the present, it is events from 1950 to the present that have the greatest reliability (Kasischke et al. 2002)).

The detailed analysis for fires occurring between 2002 and 2008 included the use of a Landsat differenced Normalized Burn Ratio (dNBR) product (accessible through the Monitoring Trends in Burn Severity Program: http://www.mtbs.gov/). This product was used to map burned and unburned areas within fire perimeters following Kasischke and Hoy (2012) and is based on the normalized burn ratio originally developed by López-Garcia and Caselles (1991). In our analysis, regions obscured by cloud cover or smoke, as well as scan line corrector off areas (regions lacking data due to the mechanical failure of a component of the Landsat 7 ETM+ satellite), were not included (these areas represented less than 1% of the dataset). Following creation of the 2002-2008 burned area dataset, the past fire events (1950-2001) were overlaid with the areas burned in recent fire events to determine the FFI (Figure 2-1).

Based on this approach, FFIs of approximately 60 years or less (considered short- to intermediate- fire-free intervals, or S/I-I) were the focus of this study, corresponding to fire events from 1950 onwards.

Seven main types of areas derived from the analyses of the geospatial datasets were considered:

1. Fire perimeter area – the total vegetated burned and unburned areas within the MTBS provided 2002-2008 fire perimeters (also called the total fire impacted area by others (Kasischke and Hoy 2012))
2. Fire perimeter burned area – the area of burned vegetation within the MTBS provided 2002-2008 fire perimeters
3. Fire perimeter unburned area – the area of unburned (*e.g.* – not burned between 2002 and 2008) vegetation within the MTBS provided 2002-2008 fire perimeters
4. Short- to intermediate- fire-free interval (S/I-I) fire impacted area – the total burned and unburned vegetated area within the 2002-2008 fire perimeters which previously experienced fire between 1950 and 2001
5. S/I-I burned area – the total vegetated burned areas which burned in both 1950-2001 and 2002-2008

6. Long fire-free interval (LI) fire impacted area – the total burned and unburned vegetated area within the 2002-2008 fire perimeters which did not previously experienced fire between 1950 and 2001 based on the LFDB
7. Long fire-free interval (LI) burned areas – the total vegetated burned areas which burned only in 2002-2008 based on the dNBR product, and which did not burn between 1950 and 2001 based on the LFDB

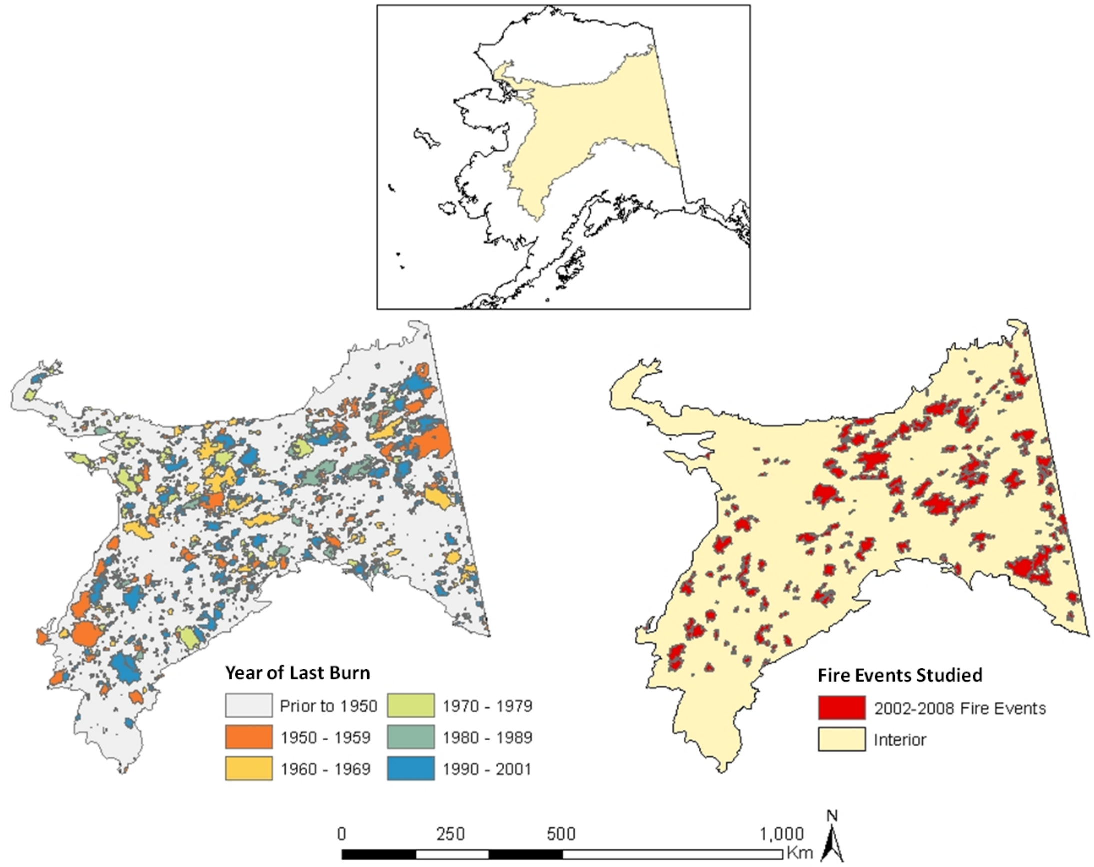

Figure 2-1: Study region and fire events analyzed. Overview of Alaska including the interior region studied within this paper (top). Time of Last Burn Product showing the decade fire was last exhibited on the landscape for the interior regions of Alaska (bottom left). Fire events from 2002 through 2008 included within this study (bottom right).

Table 2-1: Summary of fire events, fire perimeter areas and short- and intermediate- fire-free interval (S/I-I) areas used in this study. Values are in 10^3 km^2 unless otherwise noted. Only vegetated areas, and areas classified as burned or unburned, within the 2002-2008 fire events used during this study are included in the tabulations. See Section 2.2.1 for discussion of the different area types assessed.

		Fire Perimeter Area of 2002-2008 Events Studied			S/I-I Fire Impacted Areas within 2002-2008 Fire Events			S/I-I Percentages		
Year	No. of Fire Events	Burned	Unburned	Total Area	Burned	Unburned	Total Area	S/I-I Fire Impacted Area within 2002-2008 Fire Perimeter Area	S/I-I Burned Areas within 2002-2008 Fire Perimeter Area	S/I-I Burned Areas within 2002-2008 Fire Perimeter Burned Area
2002	27	6.00	0.93	6.93	1.27	0.33	1.59	23	18	21
2003	8	1.44	0.22	1.66	0.19	0.05	0.25	15	12	14
2004	41	15.78	4.00	19.78	2.52	1.23	3.75	19	13	16
2005	59	12.01	2.27	14.28	2.97	1.03	4.00	28	21	25
2006	7	0.50	0.16	0.65	0.01	0.00	0.01	1	1	1
2007	20	0.67	0.06	0.73	0.13	0.01	0.14	19	18	19
2008	5	0.25	0.05	0.30	0.10	0.03	0.13	44	34	40
Total	167	36.64	7.68	44.32	7.18	2.68	9.86	22	16	20

2.2.2 Vegetation, Topographic, and Seasonal Variation in Fire Activity

Following the methodology of Kasischke and Hoy (2012), the landscape was partitioned into six vegetation classes including coniferous forest, deciduous forest, mixed forest, high shrub, low shrub and nonwoody vegetation (Table 2-2). These vegetation classes were based on the Multi-Resolution Land Characteristics Consortium National Land Cover Dataset (NLCD) (Homer et al. 2004) which has an overall accuracy of 76% (Selkowitz and Stehman 2011). A U.S. Geologic Survey digital elevation model (NED 2009) was used to determine upland, well-drained, areas as well as lowland, poorly-drained, areas within each fire event through the derivation and analysis of slope, aspect, and elevation in conjunction with vegetation (Barrett et al. 2011, Kasischke and Hoy 2012). To be consistent with the available digital elevation model data, the spatial resolution of all additional data layers was resampled to 60 m (Kasischke and Hoy 2012).

Table 2-2: Vegetation types used in this study.

National Land Cover Dataset Category	Vegetation Type*
Evergreen forest	Coniferous forest
Deciduous forest	Deciduous forest
Mixed forest	Mixed forest
Dwarf scrub	Low shrub
Shrub/scrub	High shrub
Woody wetlands	High shrub
Grassland/herbaceous	Nonwoody vegetation
Sedge/herbaceous	Nonwoody vegetation
Moss	Nonwoody vegetation
Emergent herbaceous wetlands	Nonwoody vegetation

*Similar to the fuel types used by Kasischke and Hoy (2012).

As the focus of this research effort was on the boreal forests and vegetated areas of Alaska, only vegetated areas, as well as areas which were classified as burned or unburned (areas of cloud/smoke were removed), were considered when analyzing the fraction of burned area (FBA) and other variables considered during the study. Vegetated areas comprised 97.3% of the interior boreal region of Alaska, and made up over 99% of the areas within the perimeters of the 2002-2008 fire events studied here.

Following Turetsky et al. (2011b), areas were grouped into early (prior to July 31st) and late season (occurring post-July 31st) burning to account for broad seasonal patterns occurring throughout the fire season. This seasonality classification was based on Moderate Resolution Imaging Spectroradiometer (MODIS) Active Fire Hotspot data from the MODIS Rapid Response System (Giglio et al. 2006). As the fire season progresses in interior Alaskan boreal regions, the active layer (the top layer of soil underlain by permafrost which thaws during the growing season and refreezes during the winter months) deepens, generally leading to drier site conditions in late-season burns (Kasischke and Johnstone 2005, Turetsky et al. 2011b). Additionally, a measure of fire weather (the drought code) was analyzed over the years of this study to ensure that the early and late season groupings were sufficient. The drought code (DC) is indicative of fuel moisture conditions in the deep compacted organic soil layers found in boreal forests (Turner and Lawson 1978). Weather station data in interior Alaska (www.raws.dri.edu/akF.html) showed that during the study period (2002-2008) early season and late season fire weather differed. The mean DC increased throughout the fire season from 217.5 ± 8.1 (error represented as standard error, SE) during the early season to 370.9 ± 22.6 in the late season, indicating increased site dryness later in the season.

2.2.3 Data Analysis

Using the burned and unburned regions of each fire event, we determined the FBA within these fire perimeter areas (impacted by fire between 2002 and 2008). Then, through combining the FBA dataset with the time of previous burn dataset (based on fire events from 1950-2001), the FBA for S/I-I burned areas and LI burned areas within the recently burned 2002-2008 dataset of fire perimeter areas were determined. The overall FBA for each 2002-2008 fire perimeter area was also determined (for 167 fire events in total), and the mean and SE were then calculated based on these 167 events. Then, as the analysis was limited by the amount of S/I-I area present within the individual 2002-2008 fire perimeters sampled, S/I-I fire events of different FFIs were grouped into 5 year bins to avoid issues with inconsistent sample sizes across different FFIs for the linear regression and random forest analyses (summaries of these data are presented in Table 2-1). Samples with less than 100 pixels (36 ha) were considered to be too small and were removed.

Simple linear regression was used to analyze the FBA as a function of FFI and vegetation patterns relating to FFI. The influence of fire occurrence variables (including FFI, topography, vegetation and season of burning) on FBA was assessed using R statistical software (version 2.15.2) and the ‘randomForest’ package. The analysis included 500 regression trees and one variable input randomly sampled at each split, consistent with past approaches using random forest analysis (Breiman 2001). Variable importance was assessed using mean square error (MSE). Regression trees allow for flexibility in the analysis not always available in traditional linear regression and least squares analysis, as this machine learning approach is able to utilize potentially correlated datasets (Breiman 2001, Barrett et al. 2011). This type of analysis has been recently applied in boreal regions to assess fire severity (Barrett et al. 2011) and the influence of fire on successional trajectories (Johnstone et al. 2010b).

2.3 Results

2.3.1 Patterns of burning in S/I-I

The FBA was different between S/I-I areas and the fire perimeter area as a whole. The overall FBA within the 2002-2008 fire events studied was 84.3% ± 0.9%, where the fraction was lower for S/I-I areas within the 2002-2008 fire perimeter area (FBA = 76.5% ± 1.6%) and higher for LI areas within the fire perimeter area (FBA = 85.7% ± 0.8%).

While LI stands (those >60 years old) had a higher FBA than the S/I-I stands, S/I-I areas were still highly impacted by fire within the 2002-2008 fire events studied. Of burned areas in recently occurring fire events (burned between 2002 and 2008), 7.18 x 10^3 km^2 were last burned between 1950 and 2001 (Table 2-1). S/I-I fire impacted area (both burned and unburned areas within fire perimeters which last experienced fire between 1950 and 2001) represented 22% of the total area studied within the 2002-2008 fire perimeters area. S/I-I burned areas are prevalent within the 2002-2008 fire perimeter burned area (representing approximately 1/5th of the fire perimeter burned area), but are somewhat less prevalent within the fire perimeter area (Table 2-1). The S/I-I burned areas within the 2002-2008 burned areas were primarily from the large fire year of 2002 (18%) and the ultra-large fire years of 2004 (35%) and 2005 (41%) (Table 2-1).

2.3.2 Fire-free Interval Influence on Susceptibility to Burning

While differences between LI and S/I-I burning are evident, a picture of gradual change over time emerges when examining the overall relationship between FFI and FBA. A linear regression model between FFI and the FBA of all vegetation within the 2002-2008 fire perimeter shows a moderate correlation (R^2 =0.59, $F_{1,9}$=13.07, p=0.006), however a logarithmic transformation of the FFI dataset shows stronger correlation with FBA (R^2 =0.67, $F_{1,9}$=18.35, p=0.002; Figure 2-2, see section 2.4 for a discussion of the ecological principles related to this result). The data show that FBA drops sharply for FFIs less than 25 years (*e.g.* SI fires), and then increases gradually as a function of FFI, reaching levels similar to those outside of recently burned areas as FFI approaches 60 years.

2.3.3 Variables Controlling Fraction of Burned Area

In the random forest analysis, 31.0% of the variance between the fire occurrence variables (FFI, vegetation type, topographic position and season) with FBA was explained (mean of squared residuals = 0.02). The plot of variable importance (Figure 2-3), a measure of the prediction accuracy of the model, showed FFI to have the highest significance in the model (removing this variable would cause a 27.6% increase in the mean square error (MSE) of the model). Vegetation was moderately important in the random forest model, and its removal would have led to a 17.0% increase in the MSE, although topography and fire season were not significant variables in the model (-1.3% and -6.0% increases in MSE, respectively).

An analysis of the partial plots (Figure 2-4), which show graphical depictions of the marginal effect of each variable on the FBA, indicate an effect of FFI on FBA, although little effect was seen related to the other variables (*i.e.* – the importance of the six different vegetation types analyzed within the vegetation variable did not vary considerably). In fact, removing topography and season from the model and using only FFI and vegetation resulted in an increase in the variance explained by the model (43.6% variance explained, mean of squared residuals = 0.02). The partial plot of FFI did show that a short FFI (~10 year interval) has less impact on the FBA than does an intermediate FFI (~ >30 years), which is consistent with the linear regression model showing FBA to drop below FFIs of ~25 years (Figure 2-2). Combined, the plot of variable importance and the partial dependency plots indicate that it was FFI, associated with fuel availability (with older stands having greater biomass accumulation (Yuan et al. 2012)), that was most strongly influencing FBA in this analysis. .

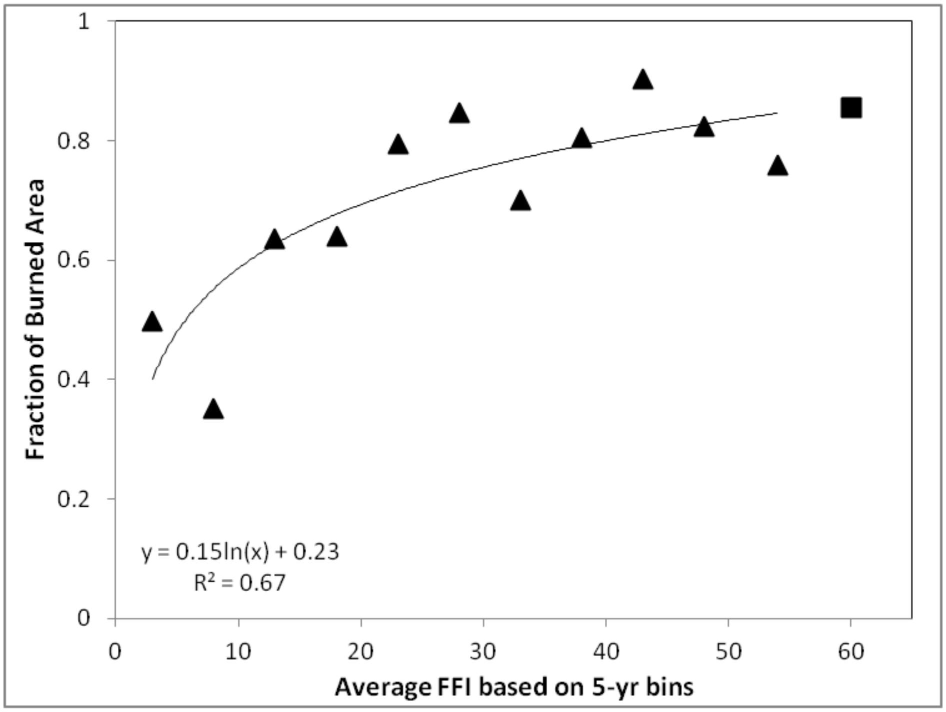

Figure 2-2: Relationship between Fraction of Burned Area and FFI. The fraction of burned area within the fire events from 2002-2008 is compared with the fire-free interval (FFI). The square at FFI >60 indicates FBA for all LI regions within the fire impacted areas studied.

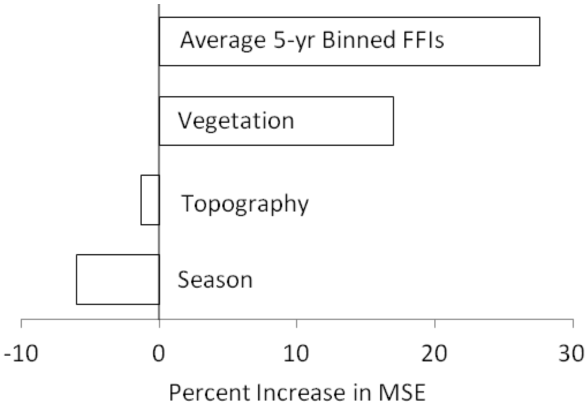

Figure 2-3: Variable importance based on the prediction accuracy of the model if different variables are removed from the analysis. An increase in the mean-square error (MSE) is associated with a decrease in the accuracy of the model based on the prediction error and the standard deviation of the differences between different trees within the model.

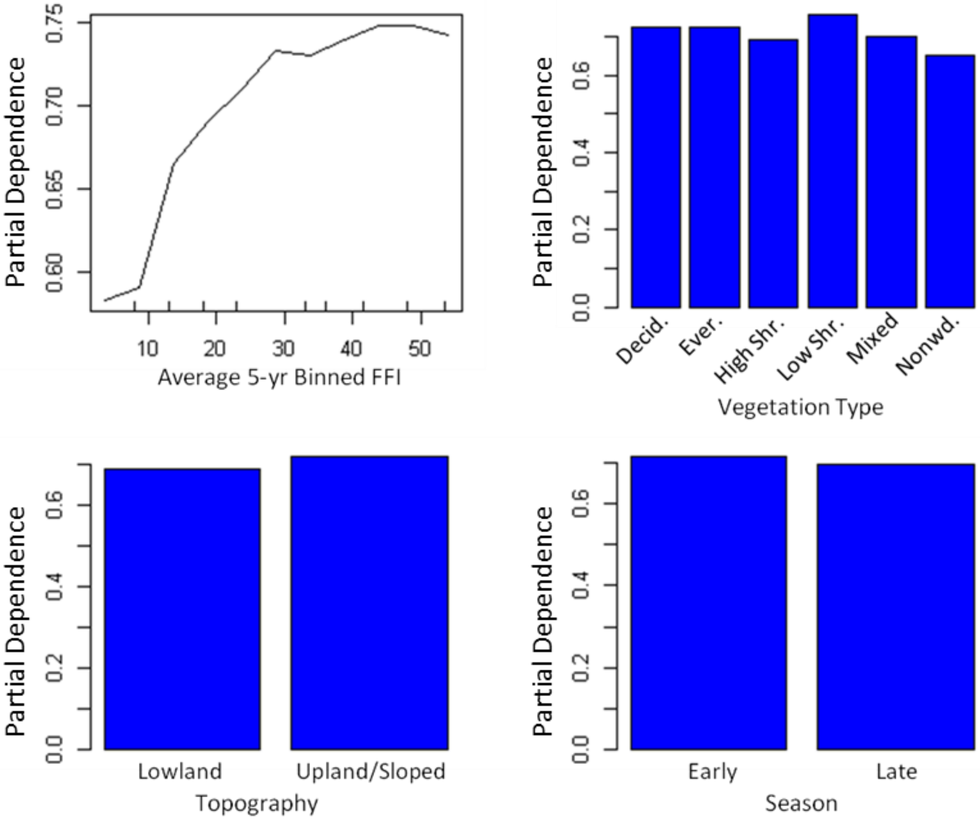

Figure 2-4: Random forest partial plots which show partial dependence on each of the variables, in order of importance.

2.3.4 Vegetation Regulation of Burned Area

Differences in burned area related to vegetation were most associated with coniferous forest and high shrub vegetation types (Figure 2-5). These two cover types were the most prevalent within the interior of Alaska (representing over 75% of vegetation in interior Alaska), and also had the greatest amount of burning. The other fuel types (deciduous, mixed, low shrub and non-woody vegetation) each represented less than 10% of the vegetation cover in the interior of Alaska and the 2002-2008 fire perimeter area. Coniferous forests, which have a complex fuel matrix that increases their susceptibility to burning, did in fact burn more frequently than their relative composition across the interior boreal landscape (representing 29% of the boreal Alaskan interior landscape, but almost 43% of the total fire perimeter burned area). Coniferous forests within S/I-I regions of the fire events burned less than those in LI areas (23% and 47%, respectively). In S/I-I stands, it was the high shrub vegetation which burned most often (almost 58% of S/I-I area burning).

As fuel type/vegetation was correlated with FBA, an additional investigation of vegetation patterns within the fire events was performed. Differences in forested and non-forested areas within S/I-I areas (Figure 2-6) corresponded with the successional trajectories typical of boreal forest vegetation (Van Cleve and Viereck 1983). As FFI increases, so does the fraction of forest cover represented within S/I-I impacted areas ($R^2 = 0.37$, $p < 0.05$; Figure 2-6). Ultimately, the fraction of forested area becomes more dominant than non-forested area at an FFI of about 50 years. With longer FFIs, this trend in FBA continues and eventually stabilizes (*e.g.* – see changes in biomass and foliage growth with stand age by Yuan et al. (2012)), until disturbance again begins the succession cycle with an increase in non-forest cover.

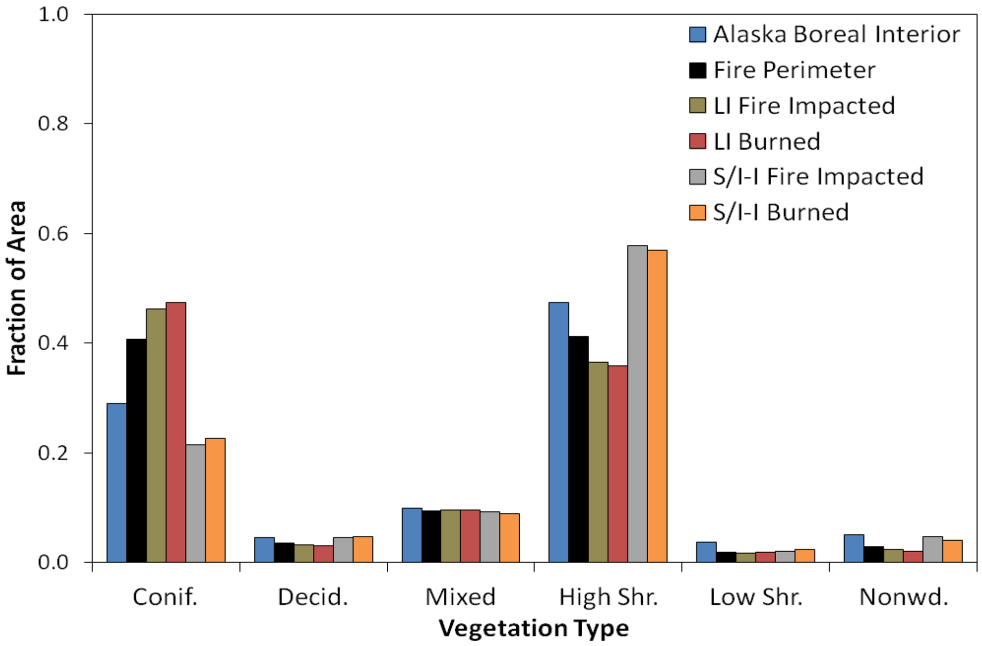

Figure 2-5: Vegetation patterns within 2002-2008 fire events. The fraction of vegetation types within the landscape units studied. Only vegetated areas within the interior were considered when calculating the fraction of the interior and only vegetated burned and unburned areas within the 2002-2008 fire events were considered for the remaining fractions. See Section 2.2.1 for discussion of the different area types assessed.

2.4 Discussion

Recent research in Alaska's boreal region has suggested that important linkages exist between climate, fire, and vegetation (Kelly et al. 2013). Some have questioned if the forests of this region have reached an ecological threshold with respect to vegetation controls on fire activity (Mann et al. 2012), with changes occurring in post-fire vegetation succession related to changes in the fire regime. Climate in Alaska has warmed over recent decades (Hinzman et al. 2005), and during this time increases have been seen in burned area (Kasischke et al. 2010) and alterations have occurred in post-fire succession

(Johnstone et al. 2011). In this geospatial analysis, we analyzed some of the issues related to the fire regime in Alaska to better understand how fire frequency is impacting these boreal forests. It was found that burning after only short- to intermediate-intervals is occurring relatively frequently (20% of all burned areas), and since burned area is projected to increase in coming decades (Mann et al. 2012) it is likely that more S/I-I burning will occur, potentially altering fire and vegetation dynamics even further.

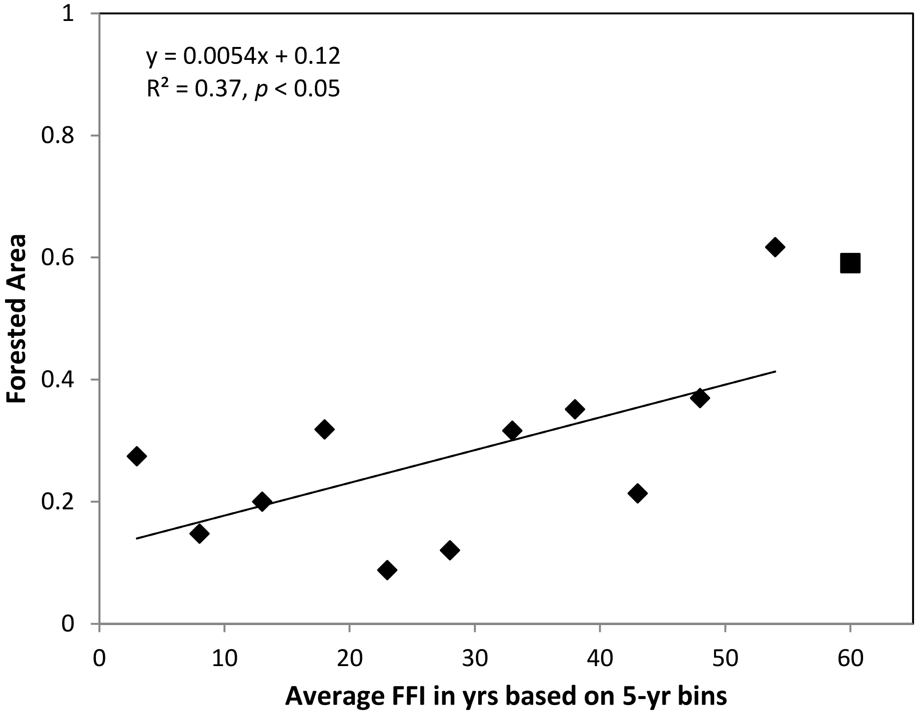

Figure 2-6: Relationship between Forested Area and FFI. Changes in the fraction of short- to intermediate-interval (S/I-I) fire impacted area across fire-free interval (FFI) for forested (evergreen, deciduous and mixed vegetation types) regions located within the fire events studied. Linear regression line is shown for forested vegetation cover types of different FFIs within the 2002-2008 fire perimeters. The square at FFI >60 indicates forested area for all LI regions within the fire impacted areas studied.

In this study, it was also seen that there is a strong relationship between FBA and FFI (Figures 2-2 and 2-4). FBA drops sharply for FFIs less than 25 years (*e.g.* SI fires), and increases gradually as a function of FFI, reaching levels similar to those outside of recently burned areas as FFI approaches 60 years. This relationship follows the stages of successional trajectories within black spruce forests as described by Van Cleve and Viereck (1983). During the first phase (first 20-30 years of development) shrubs initially grow on the sites, but the slower growing black spruce seedlings eventually establish themselves. After 20-30 years, black spruce saplings become co-dominant with shrubs. And finally, around 50-60 years post-disturbance, spruce becomes the dominant vegetation cover, with mature forests occurring after around 60 years. The logarithmic relationship illustrated in Figure 2-2 (and also visible in Figure 2-4) represents a logical response of fire susceptibility in this ecosystem. The change in the curve around 25 to 30 years represents a threshold below which fuel types and loads are too low to sustain fire. After 25 to 30 years, the increase in spruce biomass supports greater fire activity, as reflected in the continuing increase in FBA. The logarithmic relationship between stand age and biomass accumulation for Alaskan boreal forest vegetation shown by Yuan et al. (2012) also supports this hypothesis.

Two of the characteristics that are thought to control fire activity (topography and fire season) were not correlated with FBA in the S/I-I areas, although past research has shown the importance of these factors in controlling fire severity in mature black spruce stands (Kane et al. 2007, Kasischke et al. 2010, Barrett et al. 2011, Turetsky et al. 2011b). In this study, it was found that FFI (which is correlated with vegetation type and fuel build-up (Genet et al. 2013, Kelly et al. 2013)) influenced the fraction of burned area. This result highlights the importance of fuel type and availability over fuel conditions controlled by topography and fire season (such as moisture content) in determining fire behavior. In the discussion regarding the influences on fire behavior highlighted by a number of studies, our results support the research of Cumming (2001), in which it was found that fuel type influenced fire behavior, over the research of Bessie and Johnson (1995) (where weather was the dominant driver of fire behavior).

FFI was the most significant factor found in the random forest analysis of FBA, however there was a considerable amount of variance unaccounted for by the model, some of which could be due to uncertainty in the geospatial and remote sensing datasets used. The land cover dataset, as a national dataset, uses general categories for vegetation across large regions. In this dataset, the threshold for a region to be considered within a forest category (such as coniferous or mixed forest) includes trees >5 meters; however in interior Alaska this is not always an accurate representation of a forest. It has been estimated that over two-thirds of all forest cover in the boreal region of Alaska could be considered sites dominated by black spruce forest (Turetsky et al. 2011b), and many mature black spruce trees reach only between 4 and 5 m in height (Hollingsworth et al. 2006), meaning that they would be excluded from the NLCD forest category. It is very likely that the high shrub vegetation category used in our study includes areas of immature coniferous and deciduous forests, and could even include misclassified mature coniferous forests. An additional source of uncertainty stemming from the geospatial datasets used is that of burned and unburned areas within fire perimeters for 1950-2001. Only fire perimeter boundaries are known for this historic dataset of fire events in Alaska, thus all area within the each fire perimeter is considered burned. However, based on the analysis included here for the 2002-2008 fire events, the FBA within fire perimeters is only 84.3% ± 0.9%. This could be resulting in an overestimation of past burning and thus a decreased perceived FFI between fire events.

Others have discussed important climate-fire-vegetation dynamics recently emerging in the Alaskan boreal region (Johnstone et al. 2011, Mann et al. 2012, Kelly et al. 2013). Of major importance are the feedbacks between post-fire shifts in vegetation composition and future burned area. Increases in burn severity and burned area are causing post-fire vegetation shifts from coniferous forests to deciduous forests and herbaceous shrublands (Johnstone et al. 2010b, Mann et al. 2012, Kelly et al. 2013). In our study, it was found that shrubland areas represent the largest vegetation class in interior Alaska (possibly due to the NLCD sampling scheme); however these shrubs burned less often than their representation across the interior landscape, while coniferous forests burned more often (Figure 2-5). The results of this study show S/I-I burning occurred 1/5th of the time, and this could occur more frequently with changes in climate. If coniferous forests begin to decline in this region through increased fire frequency, a threshold may be reached where the region will lack the high abundance and connectivity of coniferous forests needed to carry fire across the landscape, and could result in a decrease in future burned area (Kelly et al. 2013).

2.5 Conclusion

Alterations to ecosystem processes within the Alaskan boreal forests are inevitable in the coming decades as climate continues to change. Understanding the current changes is essential in predicting and modeling future changes. If post-fire succession is altered to favor deciduous and shrub species, the large carbon pools (such as thick organic soils) currently present in the boreal forests could decrease substantially. Other ecosystem characteristics would also be impacted, such as permafrost stability (Schuur and Abbott 2011), herbivore habitat and forage material, and even human populations living in the region. It is important that the processes occurring in S/I-I stands be better understood now so that as climate changes these regions can be better assessed.

Chapter 3: More frequent burning reduces organic soil carbon stocks in Alaskan black spruce forests[2]

3.1 Introduction

Numerous changes have been observed in the fire regime of the North American boreal forest over the past half century (Gillett et al. 2004, Kasischke et al. 2010), and climate change (including increasing temperatures and decreased rainfall during the fire season) has been cited as a possible control (Duffy et al. 2005, Skinner et al. 2006). In the last 30 years alone, annual surface temperatures in boreal regions have increased by 3 – 5°C (Chapin et al. 2000), and recent warming is likely to continue into the future (Meehl et al. 2007). In the boreal forests of Canada, an increase in summer season temperatures over the past four decades has occurred at the same time as area burned by forest fires has also increased (Gillett et al. 2004). Increases in the amount of late season burning (Kasischke et al. 2010) and the severity of late season fires (Turetsky et al. 2011b) have also been observed in the boreal forests of Alaska.

Increasing annual burned area has led to a decrease in the fire return interval (FRI, an average measure of fire frequency across broad regions) in Alaska (Kasischke et al. 2010). More area in interior Alaska burned during the 2000s than in any other single decade since the start of record keeping in the region (during the 1940s) (Kasischke et al. 2010). Prior to the 2000's, the FRI for Alaska ranged between 107 and 588 years for different Alaskan ecoregions (Kasischke et al. 2002),

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[2] Submitted to *International Journal of Wildland Fire* (Hoy et al. in review-b).

which decreased to 92 to 191 years after the extensive burning during the 2000s (Kasischke et al. 2010). At the local or landscape scale, changes in the FRI are analyzed as the fire-free interval (FFI) between fire events (Johnstone 2006, Johnstone and Chapin 2006). Commonly the FFI (the focus of this study) is used as an ecological term when applied to analyses of data collected during field research, as the time between two fire events can often be determined at a smaller spatial resolution through examination of land management records and analysis of tree rings.

Disturbance, predominantly in the form of wildland fire, can strongly influence the carbon storage and emissions within the boreal region (Kasischke et al. 1995, Harden et al. 2000, Amiro et al. 2001, Bond-Lamberty et al. 2004, Turetsky et al. 2011a, Turetsky et al. 2011b, Yuan et al. 2012). The boreal forest region is one of North America's largest terrestrial carbon stores, mainly due to the large carbon pool present in the soils of the terrestrial ecosystems found in the boreal region. The carbon pools in northern permafrost regions are believed to hold over 1.672 Tg of organic carbon (estimated to be approximately 50% of the global belowground carbon pool), where some 11% of this carbon is in the soil organic layer pool found in the top 30 cm of the organic soil layer (Tarnocai et al. 2009). Due to the short growing season and cold winter temperatures, decomposition rates across the boreal region are low, resulting in the accumulation of thick organic soil layers. The accumulation of organic soils is especially pronounced in black spruce *(Picea mariana)* forests, which generally grow under some of the coldest and wettest conditions found in the boreal region (Van Cleve et al. 1983). These forests represent

45% of the land cover in the interior of Alaska and are the prevailing forest type in Alaskan (66% of all forests) (Turetsky et al. 2011b) and Canadain boreal forests (Amiro et al. 2001).

The organic soil layers of mature black spruce forests in Alaska range from <10 to >40 cm in depth (Hollingsworth et al. 2006, Kasischke et al. 2008, Boby et al. 2010, Turetsky et al. 2011b). While this range is partially due to differences in rates of production and decomposition of plant litter (Johnstone et al. 2010a), it is also dependent on the frequency and severity of disturbance events (Turetsky et al. 2011b). These sometimes thick organic soils insulate the ground surface and allow for the development of permafrost below the surface (Viereck 1983), which in turn can affect site drainage. In mature black spruce forests, the depth of the active layer (the top layer of soil underlain by permafrost which thaws during the growing season and refreezes during the winter months) and soil moisture, in sites with permafrost are both inversely proportional to the depth of the surface organic layer *(e.g.,* sites with deeper organic layers have shallower active layers and wetter soils (Zhuang et al. 2002, Kasischke and Johnstone 2005)). While these cooler and wetter sites are generally resistant to burning, with changing climate they may become more vulnerable to deeper burning (Kasischke et al. 2010, Turetsky et al. 2011b). As the depth of the organic layer controls permafrost dynamics, and thus soil moisture, recovering forests with shallower organic layer depths may be more vulnerable to burning than mature forests, which generally have deeper organic layer depths.

Chronosequence studies in black spruce forests have been used to better understand carbon dynamics and the development of the soil organic layer (Zhuang et al. 2002, Bond-Lamberty et al. 2004, O'Neill et al. 2006, Harden et al. 2012). While Harden et al. (2012) showed carbon accumulation rates of 20-40 g C/m^2/yr for stands up to ~200 years in age, they did find that stocks of shallow carbon (the C accumulation which had occurred since the time of burn) differed among stands of different ages. Another focus of recent studies has been on changes in the soil organic layer of mature black spruce stands which burn (having an FFI of ~≥80 years); however, few studies have focused on investigating soil organic layers in frequently burning stands. Using data from stands located near the tree-line in northwestern Canada, Brown and Johnstone (2011) found that 91% of the soil organic material in forest areas dominated by black spruce cover was consumed during two fire events occurring 14 to 15 years after the previous fire. In our current research, black spruce forests in Alaska which burned twice in the last 37-52 years were investigated to better understand changes in the soil organic layer of intermediate-aged black spruce forests exposed to fire. The objectives of this study were to quantify how fire frequency affects 1) the depth of burning, 2) the residual organic layer depth, and 3) the carbon loss in the soil organic layer in the black spruce forests of Alaska.

3.2 Materials and Methods

3.2.1 Study Area and Plot Locations

This study was conducted in interior Alaska, which stretches from the Brooks Range in the north to the Alaska Range in the south and encompasses multiple topographic and permafrost gradients. The black spruce forests that were the focus of this study occur primarily in areas with discontinuous permafrost (Ferrians 1998), which can greatly influence site drainage conditions and the organic soil layer thickness.

Field observations were collected during the summer months of 2009 – 2011 to study how FFI controls the depth of burning and the amount of residual soil organic matter remaining following fire in black spruce forests. Measurements were collected in black spruce forest stands located in four intermediate-interval fire events throughout the interior of Alaska (Figure 3-1) and compared with data previously collected in long-interval fire events (Kane et al. 2007, Kasischke et al. 2008, Turetsky et al. 2011b). In each of the intermediate-interval fire events, a fire first occurred in the 1950s or 1960s, with the sites burning again in the 2000s (Table 3-1). The previously sampled long-interval stands had all been mature black spruce forests (with a FFI at least >70 years) at the time of burning in the 2000s.

For all intermediate-interval sites, data were collected in plots that were located in both burned stands and adjacent unburned stands of a similar age as determined from knowledge of past fire events at the location (Figure 3-2). Unburned stands were located in multiple topographic positions (based on slope and aspect) and were dominated by live, intermediate-aged (~37-50 years) black spruce trees, with some larger, dead, black spruce trees from the previous fire event present (Figure 3-2b). There were no live trees present in the intermediate-interval burned stands (Figure 3-2a). One indicator used in plot selection was the presence of severely weathered and charred trunks of black spruce trees which had burned in the 1950s and 1960s and remained as either standing dead or fallen dead until the time of the second fire event. Plots were selected where the intermediate-interval burned stands

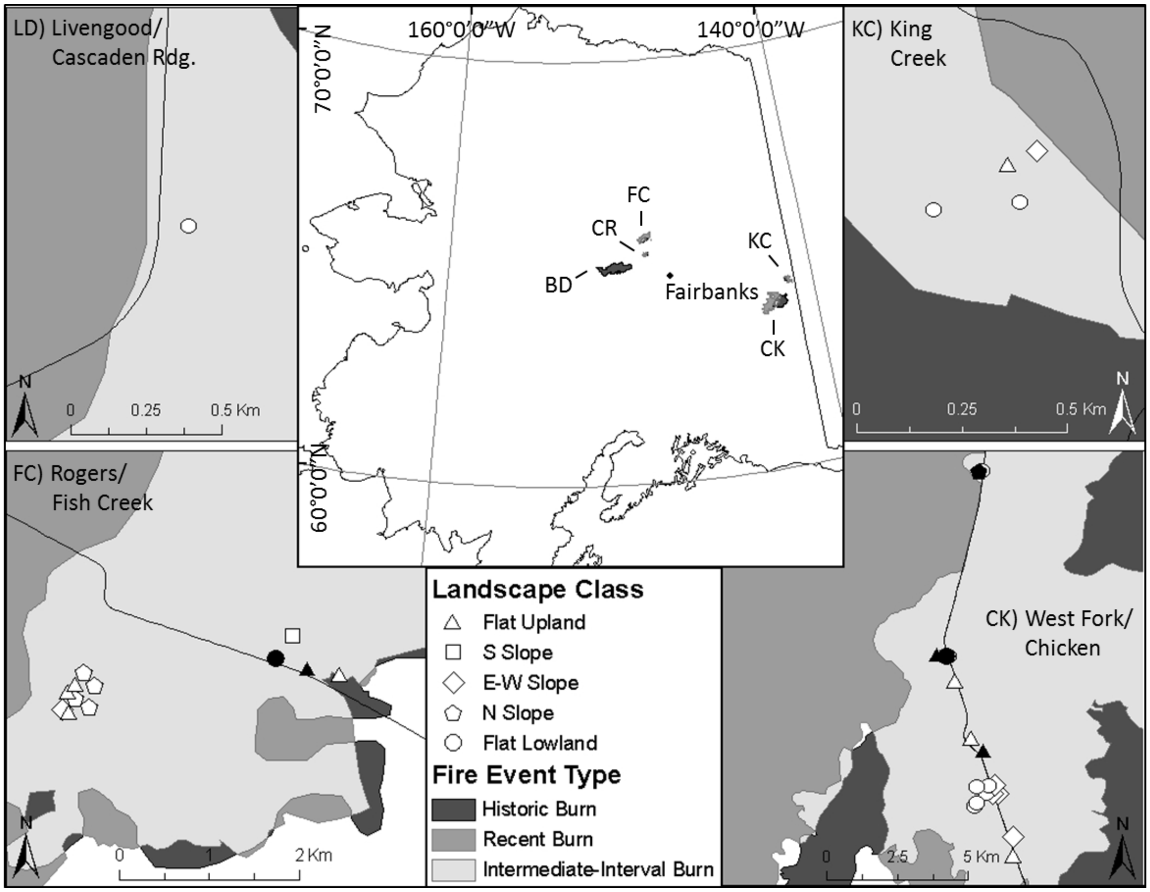

Figure 3-1: Site locations used in this study. All fire events occurred within the interior boreal region of Alaska. Individual site locations are denoted by landscape class and burn status (opened – intermediate-interval burned plot, closed symbol – historic burn only). All sites were located along the road network (thin black line) due to accessibility issues. One historic burn only site is not pictured, that in the Big Denver (BD) fire event.

Table 3-1: A summary of the intermediate-interval locations and fire events used in this study, including details of the historic (occurring in the 1950s or 1960s) and recent (during the 2000s) fire events as well as the intermediate-aged sites sampled.

	Historic Burn		**Recent Burn**		**Intermediate-aged Sites**		
Code	Fire Event	Fire Discovery Date	Fire Event	Fire Discovery Date	Burned	Unburned	FFI (yrs)
FC	Rogers	6/16/1967	Fish Creek	6/16/2005	10	2	38
KC	King Creek	6/22/1969	King Creek	6/22/2004	4	--	37
LD	Livengood	6/4/1958	Cascaden Rdg.	6/3/2010	1	--	52
CK	West Fork	7/23/1966	Chicken	6/15/2004	14	4	38
BD	Big Denver	6/16/1969	--	--	--	1	--

had been dominated by black spruce trees both prior to the historic burn (in the 1950s and 1960s) and the more recent burn (in the 2000s).

Individual plots were located within the four intermediate-interval fire events studied, consisting of an area at least 30 by 40 m on the same topographic position with similar fire severity. As site accessibility is an issue in Alaska, data collections were restricted to areas near highways and other roads accessible to field vehicles and hiking short distances (< 2 km). All plots were located at least 100 meters from paved roads to avoid local effects of the road on the natural environment and fire behavior. Following the design of previous studies (Kane et al. 2007, Turetsky et al. 2011b), sample sites were located across different topographic positions (also referred to as landscape classes) representing a gradient of well-drained to poorly-drained areas including flat uplands (FU); south (S) facing backslopes; east and west facing backslopes (EW); north (N) facing backslopes; and flat lowlands (FL) (see Table 3-2 for a list of sites by landscape class).

3.2.2 Measurement of Organic Layer Characteristics in Burned and Unburned Stands

The sampling methods followed Kane et al. (2007) and Kasischke et al. (2008). The location of the center point of each plot was recorded using a handheld GPS unit and four photos were taken (one in each of the four cardinal directions). The general characteristics of the plot were recorded including the slope position (foot, toe, or backslope), degree of slope (using an inclinometer), elevation, aspect, and a general description of the vegetation. Date of burn from the most recent fire event was established for each plot using MODIS hotspot data (Giglio et al. 2006). Each plot consisted of a randomly-oriented (based on a random number generated for each plot between 0 and 359) 40 meter baseline perpendicularly bisected by three 30 m sample transects. The first sample transect bisected the center of the baseline, and two additional thirty meter lines, parallel to the 30 meter center line, bisected the 40 meter line at a random location between 5 and 20 m from either side of the center line (using a random number generated between 5 and 20).

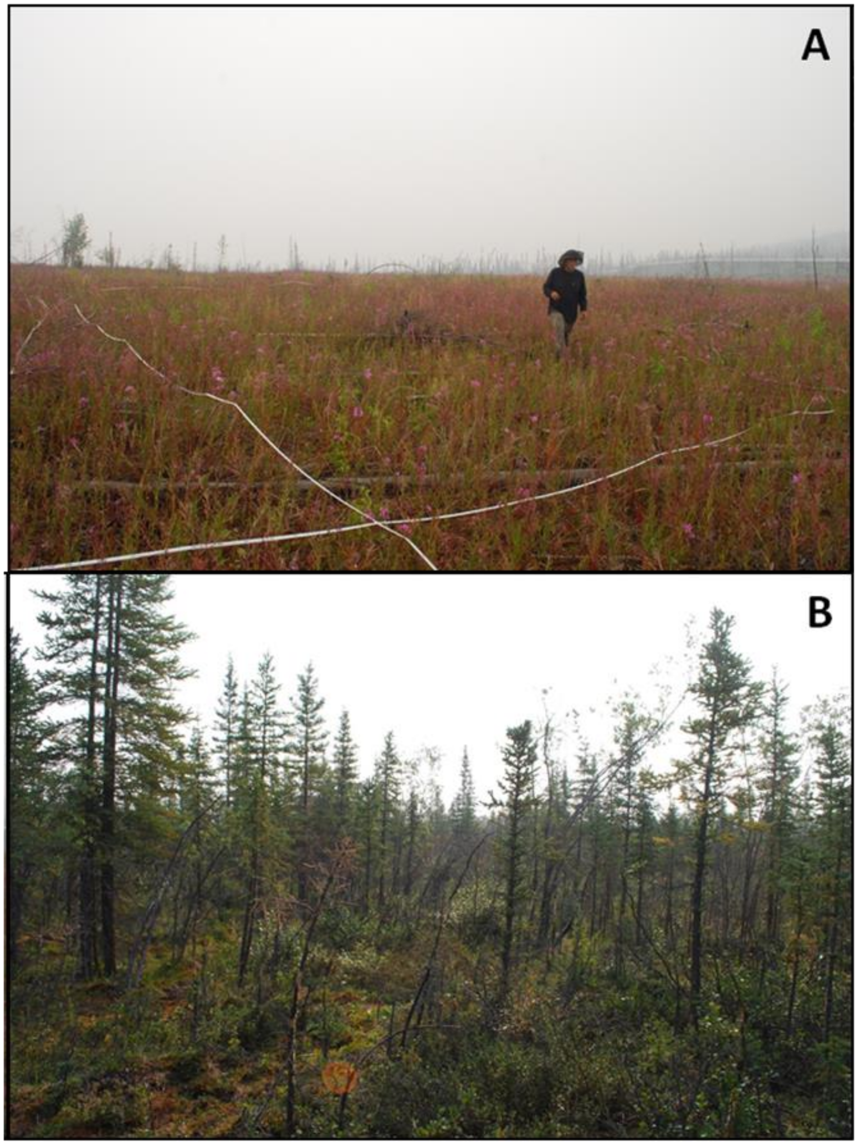

Figure 3-2: Ground photographs of field sites used during this study: A) stand that burned during the summer of 2005 and the summer of 1967; and B) intermediate-aged stand photographed in 2009 that had previously burned in 1966. (Photos collected by Elizabeth Hoy).

Table 3-2: Depth measurement results (in cm unless otherwise noted) within intermediate-interval study sites. A comparison to the long-interval sites of Turetsky et al. (2011b) is provided using the mean values based on all intermediate-interval and long-interval sites.

		Depth Measurements (cm)			
Season	Landscape Class (*n*)	Pre-fire	Post-fire	Depth of Burn	Depth Reduction (%)
Early	Flat Upland (4)	14.6 ± 1.4	4.3 ± 1.5	10.3 ± 0.7	73.0 ± 9.12
	S Slopes (1)	11.7	1.0	10.7	91.6
	EW Slopes (2)	14.0 ± 0.2	3.3 ± 1.7	10.7 ± 1.5	76.4 ± 12.0
	N Slopes (0)	--	--	--	--
	Flat Lowland (7)	18.6 ± 1.9	6.2 ± 1.2	12.4 ± 1.4	67.5 ± 5.30
Late	Flat Upland (4)	12.5 ± 1.1	1.5 ± 0.2	11.0 ± 1.0	87.8 ± 1.7
	S Slopes (0)	--	--	--	--
	EW Slope (4)	13.9 ± 0.8	2.4 ± 1.1	11.5 ± 0.5	83.9 ± 6.4
	N Slopes (4)	11.5 ± 0.3	1.1 ± 0.0	10.4 ± 0.3	90.2 ± 0.3
	Flat Lowland (3)	17.2 ± 1.6	3.8 ± 0.7	13.4 ± 2.2	76.8 ± 6.5
Intermediate-interval Site Mean (*29*)		14.9 ± 0.7	3.4 ± 0.5	11.4 ± 0.5	78.9 ± 2.6
Long-interval Site Mean[A] (*178*)		25.2 ± 0.5	9.6 ± 0.5	15.6 ± 0.5	62.9 ± 1.5

[A] Long-interval site data from Turetsky et al. (2011b).

Along each 30 meter transect, soil organic layer (SOL) and adventitious root (AR) depths (used to estimate pre-fire SOL depth, see below and Figure 3-3) were sampled every 5 meters (21 per plot). In the intermediate-interval burned plots, soil depth measurements consisted of a measurement from the top of the remaining SOL following fire to the mineral soil layer, and a breakdown of soil type was noted (including the char, fibric, mesic and humic soil layers). The AR measurements were collected by measuring the distance from the top AR to the mineral soil using black spruce trees ≥ 2 meters tall and believed to have burned during the most recent fire event (during the 2000s).

Intermediate-aged black spruce stands adjacent to intermediate-interval burned stands, or located in black spruce stands of a similar age to the intermediate-interval fire events studied, were sampled in order to aid in the development of an approach to estimate pre-fire depth using adventitious roots (Figure 3-3). Similar to the design used to make depth measurements in burned stands, SOL measurements were made in unburned stands from the top of the SOL to the mineral soil including a breakdown of soil type (moss, fibric, mesic and humic soil). As in the collection of AR data in burned stands, AR measurements were collected in the 7 unburned black spruce stands used in this study. These included the measurement of the top of the organic layer to the top AR, and from the top of the AR to the mineral soil. Using the relationship between the AR depth above the mineral soil and total organic layer depth in unburned stands, we were able to estimate pre-fire organic layer depths in burned stands following the approaches of Boby et al. (2010) and Kasischke et al. (2008).

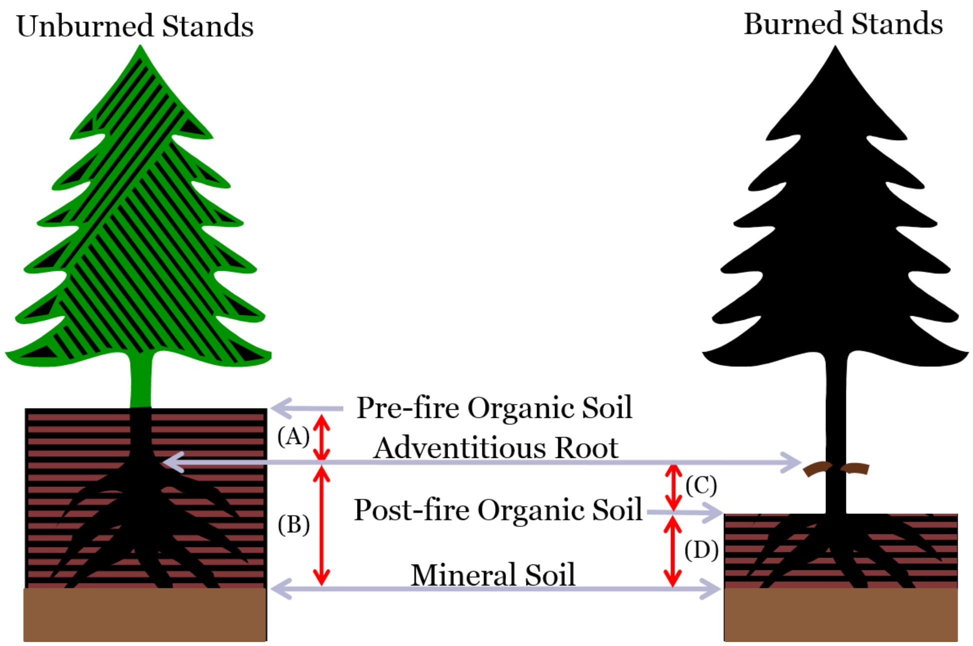

Figure 3-3: Diagram showing depth measurements made in both intermediate-aged unburned and burned plots and used to estimate pre-fire depth in burned stands. Measurements in unburned stands include (A) depth from the pre-fire organic soil to the top adventitious root (AR) and (B) from the top AR to the mineral soil; combining (A) and (B) gives the total unburned organic layer depth. Measurements in burned stands include (C) depth from the top AR to the top of the post-fire organic soil and (D) from the top of the post-fire organic soil to the mineral soil.

3.2.3 Changes in Soil Carbon

Soil organic carbon (SOC) storage and losses were estimated using empirical relationships between organic horizon depth (cm) and SOC (kg m^{-2}) developed by Turetsky et al. (2011b) from published soil data for Alaskan black spruce forests stratified by landscape (topographic) class (Table 3-3). In burned stands, the estimated depth of burn derived from AR measurements (less the char layer) was used in the analysis to account for ecosystem carbon retained in the soil as char or charcoal (Turetsky et al. 2011b).

Table 3-3: Equations used for carbon storage and losses. These equations were developed by Turetsky et al. (2011b) based on published soil data for Alaskan black spruce forests stratified by landscape (topographic) class.

Landscape Class	**Carbon Storage (in kg C m^{-2}) Equation***
Flat Upland	$Carbon=0.15*depth^{1.096}$
South Facing Slopes	$Carbon=0.109*depth^{1.403}$
East and West Facing Slopes	$Carbon =0.047*depth^{1.487}$
North Facing Slopes	$Carbon=0.135*depth^{1.185}$
Flat Lowland	$Carbon=0.073*depth^{1.423}$

*Where Carbon is carbon storage (kg C m^{-2}) and depth is organic soil depth (cm).

3.2.4 Data Analysis

The data from plots of the same landscape class located ~2 km or less from one another were combined to form a single site for statistical analyses to account for potential spatial correlation between the plots, and to be consistent with the sampling and analysis scheme used by Turetsky et al. (2011) to sample the long-interval dataset.

Organic layer depths in intermediate-interval burned sites were analyzed using two measures of fire severity (Kasischke et al. 2008): 1) depth of burn (or absolute depth reduction), the amount of organic matter which burned during the fire, and 2) percent depth reduction (or relative depth reduction), the relative amount of organic matter removed during the fire when compared to pre-fire organic layer levels (Genet et al. 2013). The characteristics of the organic layer depths found in intermediate-interval burned sites were compared with the long-interval sites previously sampled by Turetsky et al. (2011b) using linear mixed effects models, which can account for any non-normality in the dataset as well as random variables. Fixed effects included in the models were fire-free interval, landscape class, and the interaction between interval and landscape class, while the random effect of fire identity was used to account for differences among fire events used in the analysis. Other fixed effects terms (such as Julian date of the burn and annual-area burned) were not included in these models as the aim here was to investigate the effect of interval and landscape class only. These other terms have been shown to be significant in past studies (Turetsky et al. 2011b). The influence of individual fire events on the models was investigated using the Cook's D and Covariance Ratios for both fixed effects and covariance parameters of the combined long- and intermediate-interval datasets. It was determined that the main results were robust enough to account for any variation due to individual fire events. The significance of the random effects was assessed through a Wald test (Turetsky et al. 2011).

Simple linear regression was used to analyze differences between pre- and post-fire organic layer depths, depth of burn, and the date of burn in intermediate-interval burned stands. Simple linear regression was also used to investigate the relationship between adventitious root depth to mineral soil and the total organic layer depth in unburned stands (Figure 3-3), consistent with the methodology of Turetsky et al. (2011). All data are presented as means ± one standard error. The linear regressions and data summaries were conducted using S-PLUS® 7.0, while the mixed effects models were performed using SAS® 9.2.

<u>*3.3 Results*</u>

3.3.1 Estimating Pre-fire Organic Layer Depth

An initial relationship was developed between the organic layer depth and the AR depth to mineral soil using only the sample points from the seven intermediate-aged unburned black spruce sites. Based on overlapping confidence intervals for the slope and intercept of each equation, this relationship did not vary significantly from the relationship published in Turetsky et al. (2011b) to relate AR data with total organic matter depth in mature black spruce stands (linear regression model: $F_{1,317} = 3378$, $R^2 = 0.93$, $p = 0.0001$, β_0 (y-intercept) = 4.56 ± 0.35, β_1 (slope) = 1.03 ± 0.02) (Figure 3-4). As a result, this previously published relationship was used to estimate pre-fire depth in the intermediate-interval burned stands.

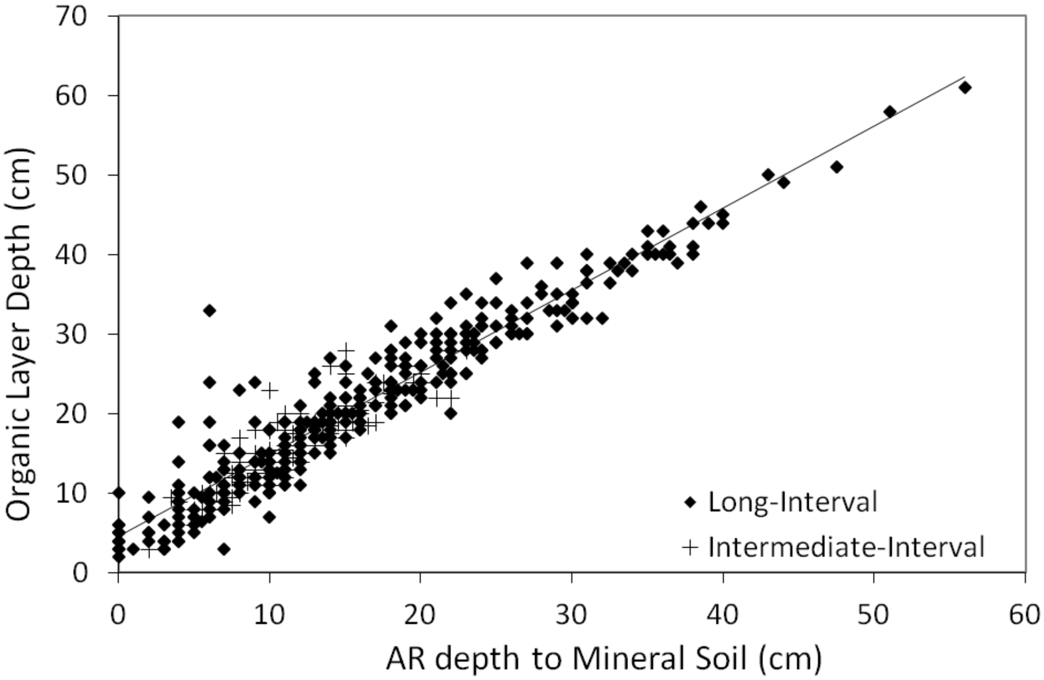

Figure 3-4: Relationship between the organic layer depth and the adventitious root (AR) distance to mineral soil for intermediate-interval and long-interval sampling points. Linear regression line is from the published equation found in Turetsky et al. (2011b).

3.3.2 Intermediate-interval Soil Organic Layer Depths

Post-fire organic layer depths in intermediate-interval burned sites ranged from 0.4 ± 0.1 cm in a flat upland site to 10.1 ± 1.2 cm in a flat lowland site, with an average post-fire depth of 3.4 ± 0.5 cm. In 40.5% of all individual sample measurements across all plots, fire had burned down to the mineral soil, leaving only a thin char layer behind. An average of 11.4 ± 0.5 cm of organic matter was consumed within the intermediate-interval burn sites (with a range of 7.4 ± 1.0 to 18.0 ± 1.2 cm), resulting in depth reduction of 78.9 ± 2.6% (Table 3-2, Figure 3-5). Pre-fire depth was found to explain 59.9% of the variation in post-fire depth across sites ($F_{1,27} = 40.39$, $R^2 = 0.5993$, $p < 0.0001$, $\beta_0 = -4.87 \pm 1.3$, $\beta_1 = 0.54 \pm 0.09$; Figure 3-6).

Based on the spatial interpolation of date of burn observed from processing of MODIS hotspot data, 14 of the sites sampled for this study are believed to have burned early in the fire season (between May and July), while 15 sites burned later in the fire season (after July 31st). Depth of burn, stratified by landscape class, did not vary greatly across early and late season intermediate-interval sites (Table 3-2). The day in year that a plot burned was not correlated with the variation in depth of burn ($F_{1,27} = 0.08$, $R^2 = 0.003$, $p = 0.78$, $\beta_0 = 12.94 \pm 5.24$, $\beta_1 = -0.0073 \pm 0.03$; Figure 3-7).

3.3.3 Comparison of Intermediate-interval and Long-interval Sites

Results of the linear mixed-effects model showed that depth of burn did not vary with fire-free interval or landscape class ($p = 0.3976$ and $p = 0.2204$, respectively). However, the percent depth reduction did vary with interval length ($p = 0.0028$, $F_{1,165} = 9.22$) and with landscape class ($p = 0.0013$, $F_{4,165} = 4.69$) (Table 3-4).

The organic layers of long-interval sites were ~70% thicker at the time of burning than those found in the intermediate-interval sites. Post-burn, the organic layers were almost 65% thinner in intermediate-interval sites than in long interval sites (Table 3-2). Percent depth reduction was 16 percentage points more (~25% greater) in intermediate-interval sites than in the long-interval sites used in this comparison (~79% and ~63% respectively, Table 3-2). The interaction between interval and landscape class was not significant in either model. However, fire identity was a significant random effect in both the depth of burn analysis and the percent depth

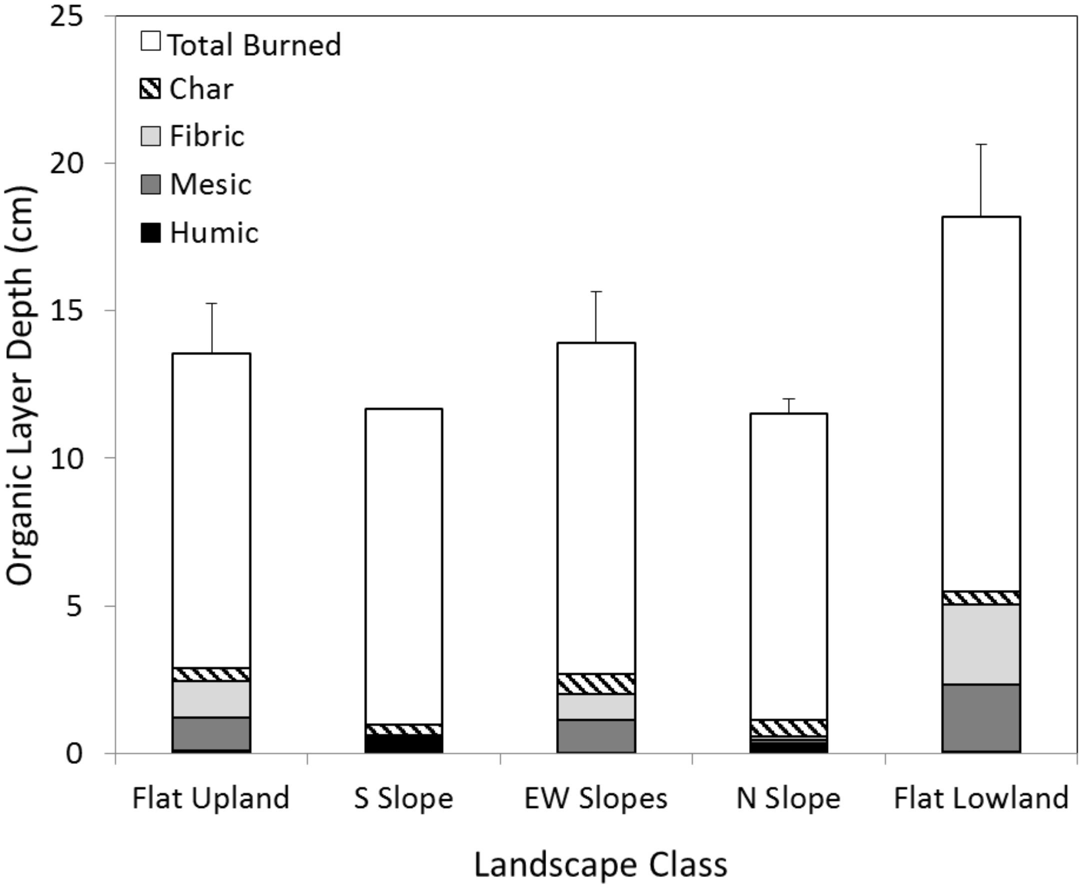

Figure 3-5: Residual organic soil layers and total burned organic soil depth estimated by adventitious root method in intermediate-interval sites sampled in this study, stratified by landscape class. Error bars are a combination of standard error for the mean values of residual and total burned organic matter depths.

reduction analysis (*p* = 0.0148 and *p* = 0.0450, respectively), suggesting that the geographic location of fires and/or aspects of fire weather could be important when predicting the effects of burning on organic layer characteristics at a regional scale.

Similar to trends in SOL depths, the post-fire SOL carbon stock was lower in intermediate-interval sites than in long-interval sites (Table 3-5). In all landscape classes where we were able to sample both intermediate-interval and long-interval sites during the early and late fire seasons, post-fire SOL carbon stock was greater in the long-interval landscape class. There was also less variability found in the intermediate-interval landscape classes. Intermediate-interval post-fire C stock ranged from 0.31 ± 0.22 kg cm m^{-2} in early season EW slopes to 1.04 ± 0.25 kg cm m^{-2} in the early season FL class (Table 3-5). While in the long-interval landscape classes, the post-fire C storage ranged from 0.58 ± 0.40 kg cm m^{-2} in late season EW slopes to 5.36 ± 1.19 kg cm m^{-2} in the late season FL class (Table 3-5).

We used these data to estimate carbon losses associated with burning. Carbon losses in intermediate-interval stands ranged from 1.61 ± 0.33 kg C m^{-2} in early-season EW slopes, to ~ 3 kg C m^{-2} in both the early-season S slope and flat lowland late-season intermediate-interval sites sampled (Table 3-5). These losses are slightly lower than those reported in Turetsky et al. (2011b) for early season fires for the different landscape classes, however, the late-season values are considerably less than those previously reported (Table 3-5).

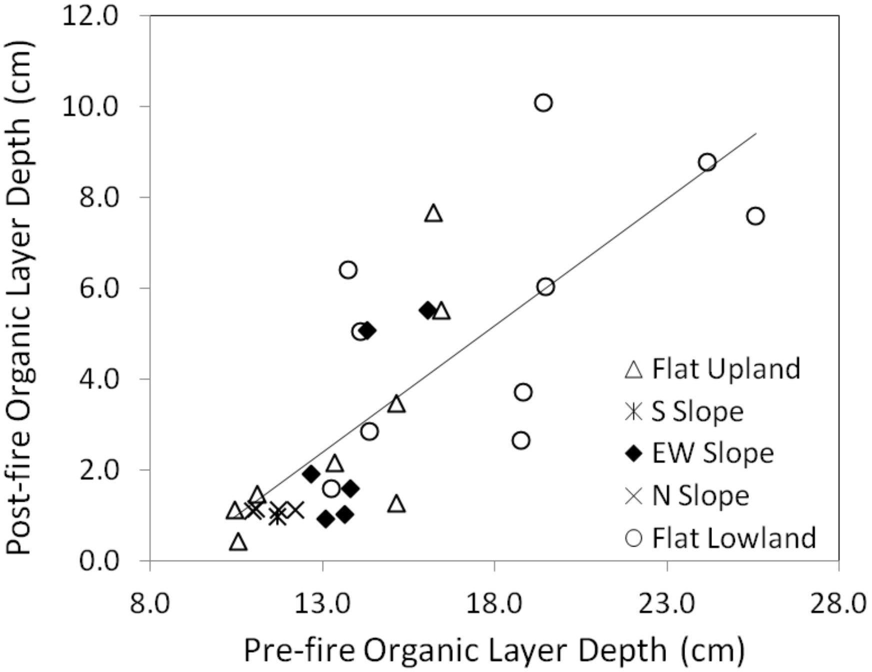

Figure 3-6: Relationship between estimated pre-fire organic layer depth and observed post-fire organic layer depth in the intermediate-interval sites used in this study.

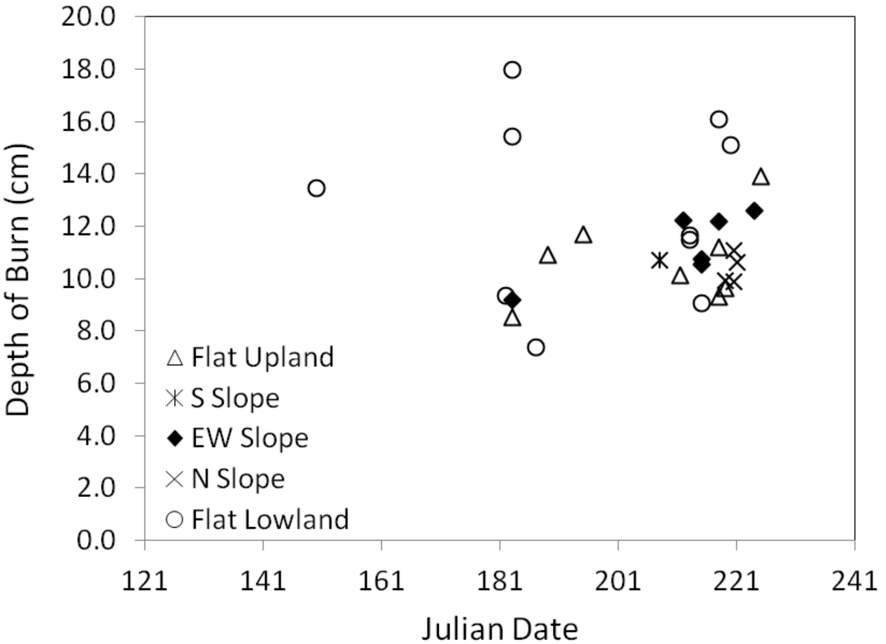

Figure 3-7: A comparison of depth of burn and date of burn for intermediate-interval burned sites used in this study.

3.4 Discussion

3.4.1 Factors Controlling Soil Organic Layer Depth of Burn

Absolute and relative depth reduction are common metrics used to discuss fire severity and fire effects in boreal regions (Barrett et al. 2011). While absolute depth reduction (depth of burn) is essential for understanding combustion rates and factors related to the fire itself (Turetsky et al. 2011b, Kasischke and Hoy 2012), relative depth reduction (percent depth reduction) is useful to discuss important post-fire impacts to the landscape. Relative depth reduction has been used to address how fire will likely affect the permafrost regime through changes in the remaining organic soil thickness, ultimately leading to potential losses in permafrost (Yoshikawa et al. 2002, Yi et al. 2009). An important question asked in this study is whether or not more frequent burning has resulted in changes in the characteristics of burning found at a site.

While landscape class has been shown to be a significant factor in controlling depth of burn in long-interval burn stands (Kane et al. 2007, Turetsky et al. 2011b), landscape class did not represent a significant control on depth of burn in the intermediate-interval sites assessed in this study (Figure 3-5). Kane et al. (2007) found that the depth of burn differed between the foot/toe slopes and the North and South facing slopes analyzed in one of the long-interval fire events studied, concluding that soil moisture was an important indicator of vulnerability to burning. Kane et al. (2007) found relative depth reduction to vary in long-interval burn stands across topographic positions (between 43% in foot/toe slope to 77% (± 4% SE) in South facing slope), while relative depth reduction was generally much greater across all topographic positions in the intermediate-interval sites studied here. One possible reason for these differences is that Kane et al. (2007) used only three slope positions, while we studied five positions and had the ability to designate flat areas as either upland or lowland based on drainage conditions at the site.

It is possible that although many of the intermediate-interval sites sampled for this current study were on different topographic positions, they could have had similar drainage conditions due to properties intrinsic to stand development. Because the organic layers in the intermediate-interval sites were shallower than in the long-interval sites used in previous studies, seasonal active layers were likely deeper and soil moisture lower than in those long-interval sites. After only 37-52 years of regrowth following fire events, the intermediate-interval sites may not yet have had adequate time to redevelop the soil organic material and permafrost layers common to mature black spruce forests. Thin organic soil layers or thick active layers result in dryer conditions, even on traditionally poorly-drained, flat lowland sites. These drier conditions could result in similar levels of burning across topographic positions in intermediate-interval events, as evidenced by the frequent occurrence of fire burning down to the mineral soil in all the intermediate-interval sites studied. Additionally, while depth of burn has been found to vary seasonally in long-interval black spruce stands (Turetsky et al. 2011b), this was not the case in the intermediate-interval stands studied here (Figure 3-7). This represents another possible indication that the intermediate-interval sites had similar drainage conditions throughout the fire season, leading to similar burn conditions whether or not a site was burned in early-season or late-season.

Table 3-4: Fire severity mixed-effects models. Depth of burn and percent depth reduction mixed-effects model parameters (including interval (years since last burn), landscape class (FU, S, EW, N, FL), and an interaction term) and results for the black spruce sites within the study region. The significance of the random effects was assessed through a Wald test.

Model	Fixed effects Term	Fixed effects F Value	DF (Num, Den)	*p*	Random effects Term	Estimate	Std. Error	Wald Z Score	*p*
Depth of Burn	Interval	0.72	1,165	0.3976	Fire identity	9.4886	4.3616	2.18	0.0148
	Landscape Class	1.45	4,165	0.2204	Residual	25.7063	2.7560	9.33	<0.0001
	Landscape Class x Interval	1.99	4,165	0.0978					
Percent Depth Reduction	Interval	9.22	1,165	0.0028	Fire identity	54.9867	32.4271	1.70	0.0450
	Landscape Class	4.69	4,165	0.0013	Residual	269.38	28.7813	9.36	<0.0001
	Landscape Class x Interval	1.41	4,165	0.2332					

Table 3-5: Carbon storage and losses. Ecosystem carbon storage and losses for intermediate-interval and long-interval fire events. A comparison to the long-interval sites of Turetsky et al. (2011b) is provided.

		Post-fire C Storage (kg C m^{-2})		C Losses (kg C m^{-2})	
Season	Landscape Class	Intermediate-interval	Long-interval ^{A}	Intermediate-interval	Long-interval^{A}
Early	Flat Upland	0.76 ± 0.29	1.79 ± 0.11	1.94 ± 0.14	2.60 ± 0.21
	S Slopes	0.11	1.4 ± 0.35	3.03	3.90 ± 0.29
	EW Slopes	0.31 ± 0.22	1.05 ± 0.33	1.61 ± 0.33	2.15 ± 0.22
	N Slopes	--	2.62 ± 0.24	--	3.33 ± 0.27
	Flat Lowland	1.04 ± 0.25	4.01 ± 0.44	2.68 ± 0.41	3.26 ± 0.34
Late	Flat Upland	0.24 ± 0.04	0.97 ± 0.16	2.08 ± 0.22	3.50 ± 0.30
	S Slopes	--	0.62 ± 0.42	--	7.11 ± 1.12
	EW Slopes	0.20 ± 0.13	0.58 ± 0.40	1.78 ± 0.12	8.29 ± 0.84
	N Slopes	0.16 ± 0.00	2.30 ± 0.56	2.16 ± 0.07	5.56 ± 0.97
	Flat Lowland	0.50 ± 0.13	5.36 ± 1.19	2.99 ± 0.66	3.58 ± 0.65

^{A}Long-interval site data from Turetsky et al. (2011b).

An almost equal number of sites burned during the early and late time periods of the fire season (14 early-season and 15 late-season sites). However we did not have replication in some combinations of topographic position by seasonality (*i.e.* there were no early-season fires on north facing slope sites and no late-season fires on south facing slope sites) and this could have affected our analyses. Turetsky et al. (2011b) found that depth of burn increased with time throughout the fire season in flat upland and all sloped sites, but not in flat lowland sites, which burned to the same degree throughout the growing season. In the intermediate-interval sites studied here, there was very little change in depth of burn throughout the growing season across the different landscape classes. These differences could be due to the difficulty in locating and accessing a wider range of sites in multiple landscape classes or could indicate that it is fuel type and not fuel condition driving fire (*e.g.* see Chapter 2).

3.4.2 Effects of Fire-free Interval

Comparisons between the long-interval sites studied by Turetsky et al. (2011b) and the sites used in this study show that, in general, long-interval sites have more organic material available to burn than intermediate-interval sites and that post-fire depths are generally greater in long-interval stands than intermediate-interval stands (Table 3-2). This is consistent with another study investigating frequently reburning stands (Brown and Johnstone 2011) which used plots located across a variety of slope and aspect positions and found pre-fire depths in short-interval stands (14-15 year fire-free interval) to range from 12.1 – 24.8 cm. The same study showed post-fire depths to be similar to those found in the intermediate-interval stands studied here. Of particular interest are the differences between absolute and relative depth reduction between the long-interval and intermediate-interval sites. Mean depth of burn does not appear to vary greatly between long-interval and intermediate-interval burn sites (Table 3-2), however relative depth reduction is much greater in the intermediate-interval sites examined for this study. This relationship appears to continue into the short-interval sites as well; the depth reduction reported by Brown and Johnstone in the short-interval plots they studied, at 75%, was similar to that reported here (78.9 ± 2.6%) across all intermediate-interval sites (Table 3-2).

3.4.3 Ecosystem Carbon Storage and Losses

Post-fire organic soil carbon stocks averaged 0.51 ± 0.08 kg C m^{-2} in the intermediate-interval sites studied here. These carbon stocks were much lower than have been previously reported. For example, C stocks of various fire-free intervals within boreal regions of Alaska and Canada have been shown to range from 2.07 - 5.74 kg C m^{-2} (Kane et al. 2007, Brown and Johnstone 2011, Turetsky et al. 2011b, Harden et al. 2012). Carbon losses estimated in this study (Table 3-5) are similar to those reported by Turetsky et al. (2011b), again indicating that while less material was stored in intermediate-interval sites, a similar amount of C was consumed in the soil organic layer during burning relative to long-interval sites. However, the results from this study clearly show that the more frequent burning of black spruce stands will result in further depletion of the large carbon reservoir that currently exists in black spruce forests.

3.5 Conclusions

As the landscape burns more frequently, there is a decrease in carbon storage in both above-ground and below-ground biomass. Here we showed that intermediate- and long-interval stands experienced similar depth of burn and C emissions, but differed in relative depth reduction due to differences in the re-accumulation of the organic soil layer. Shorter fire-free intervals in black spruce-dominated forests will result in a reduced chance of recovery for the organic soil layer, and this could lead to diminishing duff and soil thickness over several fire cycles. Additionally, thin post-fire organic soil depths could cause profound changes in the successional trajectories of black spruce forests, including an increase in dominance of deciduous or shrub species (Johnstone et al. 2010b, Barrett et al. 2011, Johnstone et al. 2011) and changes to permafrost conditions (Jorgenson et al. 2010). These changes in vegetation type would likely result in decreased burning following two fires in close succession. Further research is needed to better document post-fire recovery in intermediate-aged stands that burn.

Chapter 4: Influence of fire frequency on carbon consumption in Alaskan black spruce forests[3]

4.1 Introduction

Fire represents an important control on the carbon cycle of North American boreal forests. Wildland fires are becoming more prevalent across the landscape (Kasischke et al. 2010), resulting in changes to fire severity (Barrett et al. 2011), burned area (Kasischke et al. 2010), and fire frequency (Gillett et al. 2004, Kelly et al. 2013). Changes in the fire regime have been linked to changes in ground-layer combustion and carbon emissions (Turetsky et al. 2011b), showing that as the fire regime changes, the large organic soil carbon reservoirs common to this region are being affected.

Increased fire frequency in black spruce (*Picea mariana*) forests can have particularly wide-reaching effects on carbon storage. These forests are the dominant vegetation cover in the boreal forests of Alaska, representing two-thirds of all forest within the region (Turetsky et al. 2011b). Black spruce forests typically have thick organic soils, and in many cases these forests are underlain by permafrost, resulting in the storage of a large percentage of boreal forest carbon in this ecosystem (Schuur et al. 2008, Grosse et al. 2011). However, changes to the fire regime, coupled with changes to permafrost, will result in the release of increased amounts of soil carbon from this system (Genet et al. 2013).

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[3] Submitted to the *Journal of Geophysical Research - Biogeosciences* (Hoy and Kasischke in review).

There have been considerable efforts to improve models of the impacts of fire on soil carbon stocks in this region. A recent study by Genet et al. (2013) used a theoretical model (the Terrestrial Ecosystem Model) at a coarse spatial resolution and an annual time step to assess the total impact of fire on the region. It was found that recent changes in the fire regime are resulting in increased consumption of organic soil carbon and increased active layer thickness, which in turn, increased the decomposition of soil carbon previously protected by permafrost.

Using an alternate, bottom-up approach, Kasischke and Hoy (2012) estimated carbon emissions of wildland fires in Alaska's interior boreal region during recent small (2006-2008) and ultra-large fire years (2004). In this approach, high spatial resolution (60 meter) geospatial datasets were used to assess carbon consumption within individual fire events on a daily time scale. Both of these approaches (Genet et al. (2013) and Kasischke and Hoy (2012)) assess the impacts of fires in Alaskan boreal regions, and have focused on improving estimates of the consumption of surface organic material in black spruce forests based on Turetsky et al. (2011b), but the different approaches have yielded different results.

Even as these new approaches improve the estimation of consumption in Alaska's boreal forests, there are limitations. While estimates of the fire return interval (an average measure of fire frequency) in interior Alaska have decreased in recent decades (from 216 to 156 years) mainly due to increased burned area between 2000 and 2009 (Kasischke et al. 2010), this change is not realistically reflected in the amounts of soil organic carbon consumed during fires. Characteristics of burning in younger (immature) boreal forest stands (such as in quantifying burned area and assessing the fraction of ground-layer carbon consumed) represent uncertainties as consumption in these younger stands has not been the focus of earlier studies.

Recent research has begun to assess these two uncertainties in immature stands. The research presented in Chapter 2 has shown that over much of the past decade in interior Alaska, approximately 20% of the burned area has been in forested stands ≤ 60 years in age. This research also showed that the fraction of burned area within the fire perimeter that was burned during the past decade changed over time since the previous fire, most likely related to the changes in fuel type and amount as forests recovered from the previous fire. For example, in burned black spruce forests, there is a rapid initial revegetation by shrub species and other early colonizers, followed by the slowing and eventual stabilization of vegetative growth as mature forests develop (Van Cleve and Viereck 1983). Additionally, Chapter 3 provided comparisons of depth of burn between fires occurring in immature and mature black spruce stands. It was found that while depth of burn into the soil organic layer was similar between burned stands of these two different fire-free intervals (11.4 ± 0.5 cm in immature stands and 15.6 ± 0.5 cm in mature stands), the relative depth reduction varied as less material was initially available to burn in the younger stands but similar depths of burn occurred (relative depth reduction of 78.9 ± 2.6% in immature stands compared with 62.9 ± 1.5% in mature stands). In Chapter 3, it was also found that unlike in mature stands, depth of burning was not controlled by topographic position or the timing of the fire during the year.

Here, the approach used in Kasischke and Hoy (2012) to model carbon consumption during fire in interior Alaskan boreal forests was refined based on these new findings on burning in immature black spruce stands. The objectives of the research were to 1) estimate the burned area occurring in immature black spruce stands within the study period, 2) develop new fuel consumption values for immature black spruce, and 3) use these results to model carbon consumption during wildland fires in 2004 and 2005 in interior Alaska.

4.2 Methods

4.2.1 Overall Modeling Approach

Kasischke and Hoy (2012) developed an approach to model carbon consumption during fires in Alaskan boreal forests (here referred to as KH2012v1) which has been refined in this study (here referred to as KH2012v2). KH2012v1 followed the approach developed by de Groot et al. (2007), with the primary differences occurring in the methods used to estimate the vegetation type, site drainage, and ground-layer fuel consumption. For this study, modifications were made to the vegetation classification of burned areas and the decision rules used to calculate carbon consumption. Specifically, a new fuel type, immature black spruce forests, was added to the model in order to develop more comprehensive values for overall carbon consumption within the two fire years studied.

Figure 4-1 shows the workflow used for both KH2012v1 and KH2012v2, where the steps modified for KH2012v2 are highlighted in orange. Characteristics of the large interior boreal expanse of Alaska needed to estimate carbon consumption during fires were mapped using multiple geospatial datasets, including: (a) the National Land Cover Database - circa 2001 (NLCD), a Landsat based product (http://www.mrlc.gov/); (b) topographic information (elevation, slope and aspect) from the National Elevation

Database (NED, http://ned.usgs.gov/); (c) burned and unburned areas within fire perimeters derived from a Landsat-based delta Normalized Burn Ratio (dNBR, http://www.mtbs.gov/); and (d) a MODIS active fire (e.g. hotspot) product (Giglio et al. 2006) to determine the date of burn (see Kasischke and Hoy (2012) for specific details of these datasets). Field observations from black spruce forests were used to create decision rules for forest floor fuel consumption (FFFC) in black spruce forests and lowlands. The fire weather index (FWI) determined fuel consumption for dead and downed woody debris fuel consumption (DWDFC) and crown fuel consumption (CFC) remained unchanged from KH2012v1. The modifications used in KH2012v2 (Figure 4-1) include changes in the daily burned area assigned to specific fuel types as well as the addition of additional field observations of surface organic layers in immature black spruce forests (see Chapter 3). These additional datasets allowed for the refinement of the decision rules used to determine carbon consumption.

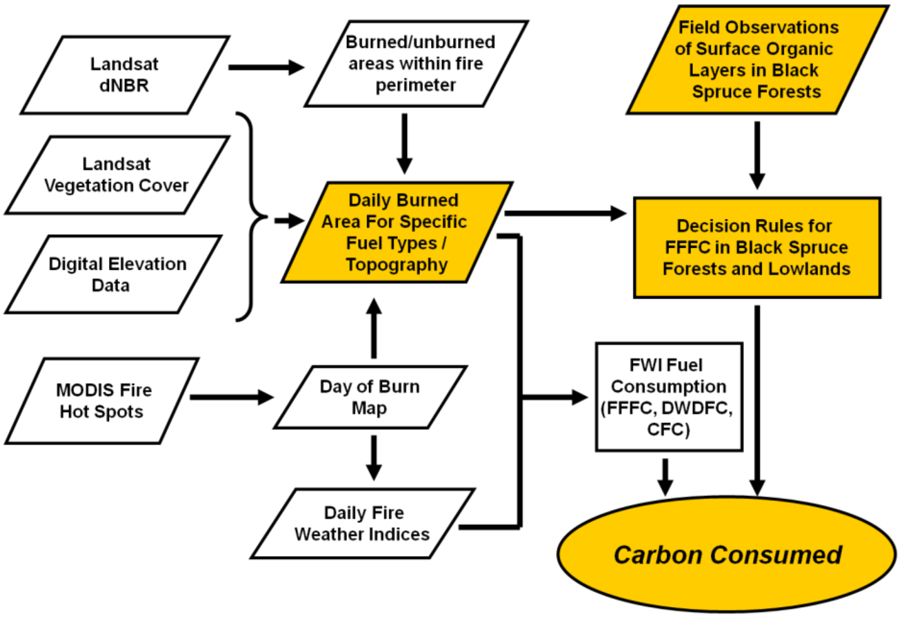

Figure 4-1: A flow diagram showing the general approach used to model carbon emissions (modified from Kasischke and Hoy (2012)). Areas where changes were made to this approach are in orange.

For this research, 100 fire events from 2004 and 2005 were analyzed (Figure 4-2). The fire events studied ranged in size from 4,058 ha to 217,789 ha and represented over 95.0% of the total burned area in 2004 and 98.4% in 2005. During these two years, over 1.5 million hectares were impacted by fire per year (2.6×10^6 ha in 2004 and 1.8×10^6 ha in 2005), making both of these years ultra-large fire years based on the classification approach of Kasischke and Turetsky (2006). As over 75% of immature forests which burned from 2002 to 2008 occurred in these ultra-large fire years of 2004 and 2005 (research presented in Chapter 2) these two fire years were chosen to be included in the evaluation of the influence of more frequent fires on direct carbon emissions resulting from biomass burning.

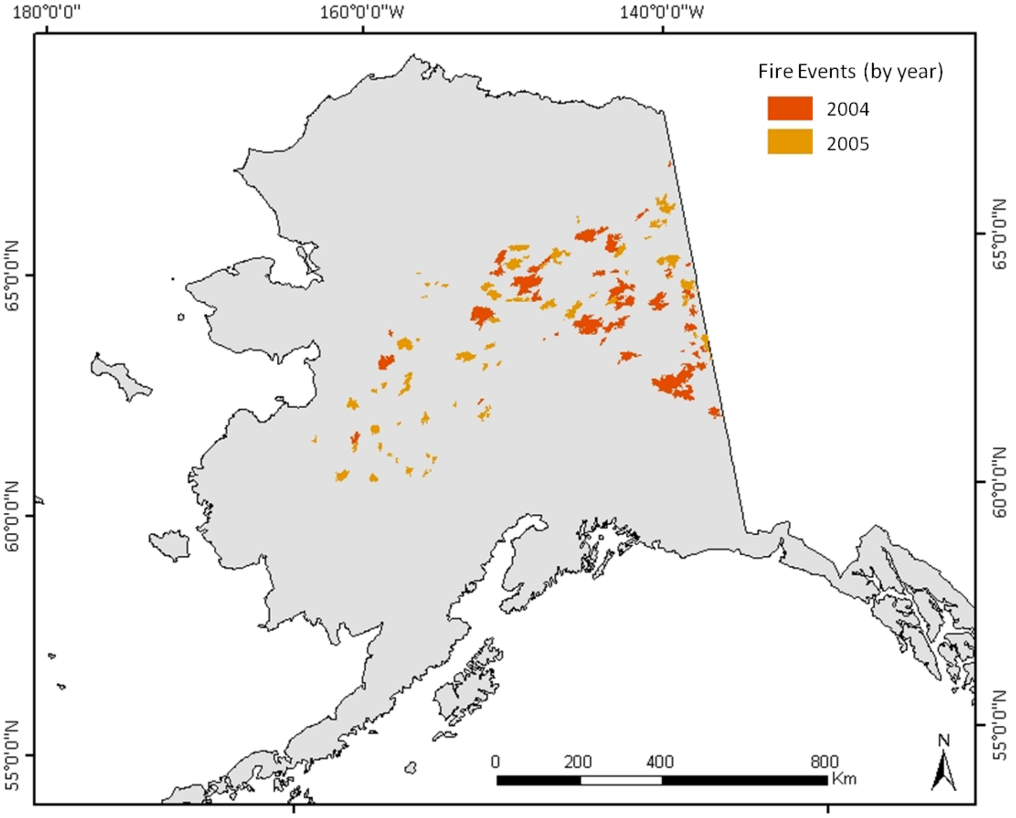

Figure 4-2: Fire events in this analysis located throughout the interior boreal region of Alaska during two ultra-large fire years.

4.2.2 Fuel Type and Area Estimates

Using the NLCD, fuel types were determined for both versions of the model (KH2012v1 and KH2012v2) (Table 4-1). Following Kasischke and Hoy (2012), this information was combined with the topographic dataset to determine upland and lowland regions for specific fuel types to create specific fuel categories (such as upland black spruce or lowland high shrub). There are 45.69 x 10^6 ha of vegetated area within interior of Alaska, and over 13% of that burned in 2004 and 2005 (Table 4-2). Within the fire events analyzed for KH2012v1, high shrub vegetation and coniferous forest (composed of both mature black spruce and white spruce (*Picea glauca*) forests) categories represented a significant portion of the vegetated areas (39% and 46% respectively). Areas recovering from recent fires represented a significant percentage (~20%) of the area burned in 2004 and 2005 (research presented in Chapter 2), and a large portion of these areas are likely to be regenerating forests that were classified as shrubs on the NLCD data set. Therefore, there is a need for better estimating fuel types within these younger stands. Such an approach was developed for this study (see 'Fuel Type Modifications' below).

4.2.3 Fuel Type Modifications

While areas of black and white spruce forests are both included in the coniferous forest NLCD cover type, it has been previously estimated that black spruce forests represent 90% of all coniferous forests in the region (Turetsky et al. 2011b). The NLCD vegetation categories (Table 4-1) included in the KH2012v1 high shrub category (NLCD categories of shrub/scrub and woody wetland) include shrubs less than 5 meters high. This category also includes young trees in early successional forest stands (Homer et al.

2004), such as recovering black spruce forests. The post-fire landscape in these recovering forests is first dominated by shrub vegetation until about 25 years post-fire (Van Cleve and Viereck 1983). Then, black spruce saplings become co-dominant with these shrubs, and finally they become the mature, dense black spruce forests between 50 and 60 years post-fire (Van Cleve and Viereck 1983). As black spruce is not the dominant vegetation cover until approximately 50-60 years post-fire, it is likely that these recovering stands are classified as shrubs by NLCD; however the underlying soil organic layer will be different between a shrub-dominant and recovering black spruce-dominant landscape.

In order to account for these black spruce stands in the early stages of recovery within KH2012v2, the area of the high shrub category was allocated into two fuel types: high shrubs and immature black spruce (Table 4-1). This reallocation of vegetation was done using stand age distribution data from Yarie and Billings (2002) and total area estimates for interior Alaska. Yarie and Billings (2002) estimated that 29.8% of black spruce stands within interior Alaska were between 0 and 49 years old. Using the total area of mature black spruce forests in the interior, derived from NLCD (Table 4-2), in combination with the percentage of immature black spruce, derived from the stand age distribution data, the total area of immature black spruce within the interior was estimated and subtracted from the high shrub vegetation type (Table 4-2). The fraction of immature black spruce classified as high shrub (23.4%) was then applied to the 2004 and 2005 fire events to estimate the area of immature black spruce within these burned areas, which in turn reduced the area of high shrub within the analysis (Table 4-2).

Table 4-1: Fuel types used in KH2012v1 and KH2012v2. Table modified from Kasischke and Hoy (2012).

National Land Cover Dataset Category	Fuel Type	
	KH2012v1	KH2012v2
Evergreen forest	Black spruce/white spruce	Black spruce/white spruce
Deciduous forest	Deciduous forest	Deciduous forest
Mixed forest	Mixed forest	Mixed forest
Dwarf scrub	Low shrub	Low shrub
Shrub/scrub	High shrub	High shrub/ Immature black spruce
Woody wetlands	High shrub	High shrub/ Immature black spruce
Grassland/herbaceous	Nonwoody vegetation	Nonwoody vegetation
Sedge/herbaceous	Nonwoody vegetation	Nonwoody vegetation
Moss	Nonwoody vegetation	Nonwoody vegetation
Emergent herbaceous wetlands	Nonwoody vegetation	Nonwoody vegetation

Table 4-2: Summary of area (in ha x 10^6) of different fuel types within the interior boreal region of Alaska and within the 2004 and 2005 fire events studied in this analysis.

Fuel Type	Interior Alaska		Total Burned Area (2004 and 2005)	
	KH2012v1	**KH2012v2**	**KH2012v1**	**KH2012v2**
Mature Black Spruce Forest	11.95	11.95	1.45	1.45
White Spruce Forest	1.33	1.33	0.16	0.16
Deciduous Forest	2.13	2.13	0.14	0.14
Mixed Forest	4.54	4.54	0.35	0.35
High Shrub	21.71	16.64	1.27	0.97
Low Shrub	1.75	1.75	0.07	0.07
Nonwoody	2.29	2.29	0.03	0.03
Immature Black Spruce	--	5.07	--	0.30
Total	45.69	45.69	3.46	3.46

4.2.4 Immature Black Spruce Carbon Consumption Values

A second adjustment in the KH2012v2 model was to both develop and incorporate ground-layer carbon consumption values for the immature black spruce fuel type. This was done since field research conducted in immature black spruce stands (*e.g.* Chapter 3) showed that carbon consumption values for these immature black spruce stands were different than the values observed for the mature black spruce stands across various topographic positions.

Using the data presented in Chapter 3, a mixed-effects model of ground-layer carbon consumption (in kg m^{-2}) in immature black spruce stands was developed to test the relationship between burn period (early and late season) and topographic position (upland and lowland), factors found to be important in ground-fuel consumption in mature black spruce forests (Turetsky et al. 2011b). This model type was used to account for random differences between the fuel consumption data based on the depth of burn measurements collected for Chapter 3 from different fire events. Based on the model (Table 4-3), it was determined that ground-layer carbon consumption was related to topography ($p<0.0005$), but unrelated to burn period ($p=0.92$). A Wald test was used to assess the random effect of fire events on the analysis, and it was found to be insignificant ($p=0.32$). As burn period was not significant, only upland and lowland ground-layer carbon consumption values were determined for immature black spruce (upland: 2.13 kg m^{-2} and lowland: 3.14 kg m^{-2}). Crown-layer and dead woody debris (DWD) fuel consumption values were not altered in this analysis, as immature black spruce and high shrub vegetation types were believed to have a similar levels of above-ground fuels.

4.2.5 Uncertainty Assessment

There are many sources of uncertainty embedded within the datasets and methods used to estimate carbon consumption during wildland fires (see French et al. 2004; Kasischke and Hoy, 2012). Uncertainties in estimates of burned area as well as carbon consumption and fuel loads all contribute to these uncertainties in total carbon consumed during fires. The uncertainty in the ground-layer fuel consumption in immature black spruce provided through field sampling (*e.g.* see Chapter 3) was lower than that associated with the high shrub category (Table 4-4).

The approach to estimate uncertainty described by Kasischke and Hoy (2012) and French et al. (2004) was used in the research presented here. In this approach, the values of each variable used in estimating carbon consumption were randomly varied using specified input coefficients of variation (CVs), where a CV is defined as

$$\text{CV} = \text{standard deviation/mean} \qquad \textit{Eq. (1)}$$

Input CVs (Table 4-4) were the same as those used by Kasischke and Hoy (2012), except we added a CV for fuel consumption in immature black spruce. We assumed that this additional input CV had a lower uncertainty than that used in high shrub vegetation as we had conducted field research in immature black spruce stands.

Using the daily burned area and average fire weather for each of the two fire years studied as a baseline, the uncertainty assessment, with associated output CVs, was completed for both versions of the model. This approach allowed for the investigation of how the refinements made to the model affected uncertainty. The error analysis was run one thousand times for both low and high uncertainty to understand sensitivity of the error in modeling ground-layer carbon consumption.

Table 4-3: Carbon consumption mixed-effects model. Model parameters and results for the short- to intermediate-interval black spruce plots studied within Chapter 3. The significance of the random effects was assessed through a Wald test.

Model	Fixed effects term	Fixed effects F Value	DF (Num, Den)	*P*	Random effects Term	Estimate	Std. Error	Wald Z Score	*p*
Carbon Consumption (kg m^{-2})	Topographic Position	15.82	1,32	0.0004	Fire Event	0.02960	0.06253	0.47	0.3180
	Burn Period	0.01	1,32	0.9214	Residual	0.4398	0.1077	4.08	<0.0001
	Topographic Position x Burn Period	0.00	1,32	0.9690					

Table 4-4: Input coefficients of variation used in the uncertainty assessment for all factors considered within the analysis. The table is the same as Kasischke and Hoy (2012), with the exception of the addition of immature black spruce (BS) ground.

Uncertainty Type	**Burned area**		FWI	**Carbon consumed/fuel loads**		
	Fraction of burn perimeter	Fuel/ topographic		BS ground	Immature BS ground	All other fuels
Low uncertainty	10%	15%	20%	15%	15%	30%
High uncertainty	15%	25%	30%	25%	25%	50%

4.3 Results

4.3.1 Ground-Layer Carbon Consumption

The refinements to KH2012v1 led to a predicted overall increase in ground-layer consumption, and thus total carbon consumption for the 2004 and 2005 fires (Table 4-5), primarily due to the replacement of ground-layer high shrub carbon consumption with immature black spruce consumption. Over 63.60 and 41.98 Tg of total carbon were released during the 2004 and 2005 fires, respectively. These refinements to the model resulted in an increase of 2.56 Tg C in 2004, and a similar increase in 2005 (2.27 Tg C) over the KH2012v1 values, which represents 4.2% more carbon release in 2004, and 5.7% more in 2005.

Table 4-5: Overall total and ground-layer total carbon consumption (in Tg). Comparison of carbon consumption values, showing both KH2012v1 and KH2012v2 ground-layer and total consumption.

Year	Type	KH2012v1	KH2012v2	Change	Percent Change
2004	Ground	52.06	54.63	+2.56	+4.9
	Total	61.04	63.60	+2.56	+4.2
2005	Ground	33.55	35.82	+2.27	+6.8
	Total	39.71	41.98	+2.27	+5.7

Most of the carbon consumption resulted from the burning of ground-layer fuels (Tables 4-5 and 4-6), consistent with the findings of Kasischke and Hoy (2012). Within the ground-layer, it was the deep organic soils of mature black spruce forests and to a lesser extent the immature black spruce forests which resulted in the high levels of consumption. These deep organic soils resulted in over 85.9% of the consumption in

2004 and 85.3% in 2005, amounts which are similar to that reported by Kasischke and Hoy (2012) for 2004 (85.7%).

Table 4-6: Carbon consumption by fuel level. Carbon consumed (in Tg) during the 2004 and 2005 fires events studied as a function of fuel level.

Year	KH2012v2 Ground	Crown	Dead Woody Debris	Mature Black Spruce Ground	Imm. Black Spruce Ground
2004	54.63	5.78	3.20	42.37	3.57
2005	35.82	3.97	2.18	23.99	3.51

The higher total C consumption estimates were produced by the refined model because average ground-layer consumption was much greater in the newly added immature black spruce fuel type than in the high shrub type (Table 4-7). Kasischke and Hoy (2012) found the average ground-layer carbon consumed for black spruce forests (namely mature black spruce forests) in 2004 to be 5.64 kg m^{-2}, which is twice the level of ground-layer carbon consumption in the immature black spruce fuel type for the ultra-large fire years studied here.

Burning of immature black spruce forests in upland areas generated greater carbon emissions than in lowland areas because lowland areas were not as prevalent as upland areas within the fire events analyzed (representing only 27.3% and 24.7% of the combined high shrub and immature black spruce burned area in 2004 and 2005, respectively). While there was a decrease in high shrub burned area of ~23% between KH2012v1 and KH2012v2 due to the correction factor applied to the later, ground-layer emissions rose by 50% or more (Table 4-8), related in part to the higher carbon consumption values in the immature black spruce fuel type as compared to the high shrub type. Aside from changes in burned area, total carbon consumption also varied as a result of differences in topography and the season of burn (Table 4-8) (see carbon consumption values (in kg m^{-2}) in Kasischke and Hoy (2012)). For example, there were less dramatic increases between the 2005 lowland ground-layer carbon consumption values from KH2012v1 to KH2012v2 (Table 4-8), as significant burning occurred late into the fire season during that year.

Table 4-7: Average ground-layer consumption (kg m^{-2}). Average ground-layer carbon consumption (kg m^{2}) during the 2004 and 2005 fire events studied. *High shrub KH2012v2 and KH2012v1 average ground-layer carbon consumption values are equal as they are based on a ratio of burned area and total consumption.

Year	High Shrubs*	Immature BS
2004	0.68	2.41
2005	0.84	2.38

4.3.2 Error Analysis

Overall, the model uncertainties (output CVs) were lower for both 2004 and 2005 in KH2012v2 than KH2012v1, however the differences were small (Table 4-9). The KH2012v1 values of uncertainty for 2004 were slightly different than the values presented in Kasischke and Hoy (2012), although this difference is possibly due to small variations in the input datasets and rounding factors used in the analysis. The lower output uncertainty in KH2012v2 is likely due to the lower input uncertainty assumed for fuel consumption in the immature black spruce fuel type as compared to the values used for high shrub vegetation (Table 4-4). In KH2012v1, the higher level of uncertainty would have been used for a greater fraction of the study area as high shrub vegetation included the area allocated to immature black spruce in KH2012v2.

Table 4-8: Ground-layer carbon consumption by fuel type and fuel category. Total ground-layer carbon consumption (Tg) for KH2012v1 and KH2012v2 fuel type and fuel category by year. Also shown are the increases in ground-layer consumption based on the KH2012v2 totals. *Change represents the change in ground-layer consumption from KH2012v1 high shrub values to KH2012v2 high shrub and immature black spruce values.

Assessment Type	Fuel Type	2004			2005		
		Upland	Lowland	Total	Upland	Lowland	Total
KH2012v1	High Shrub	2.91	1.42	4.33	2.89	2.43	5.32
KH2012v2	High Shrub	2.23	1.09	3.32	2.21	1.86	4.07
	Immature Black Spruce	2.30	1.27	3.57	2.37	1.15	3.51
Change in Ground-Layer Consumption*	Tg C	+1.62	+0.94	+2.56	+1.69	+0.58	+2.27
	Percent	+56	+66	+59	+59	+24	+43

Table 4-9: Summary of output coefficient of variations (CVs) developed from the uncertainty assessment (including both low and high output uncertainty). *The large fire year CVs from Kasischke and Hoy (2012) are provided as a comparison.

Assessment Type		All Factors (%)	
	CV	2004	2005
KH2012v1	Low	13.3	13.6
	High	21.2	21.7
KH2012v2	Low	13.0	13.1
	High	21.3	20.6
Kasischke and Hoy (2012)*	Low	13.5	--
	High	21.4	--

4.4 Discussion

Recent modeling and simulation studies have pointed to decreases in the size of the carbon sink in arctic and boreal regions, due to increased soil organic layer decomposition associated with climate change, as well as increases in fire-related emissions (Hayes et al. 2011, Turetsky et al. 2011b, Yuan et al. 2012). Process-based model studies have also been used to investigate the impacts of different aspects of the fire regime, such as the relationship of soil carbon storage to fire severity (Genet et al. 2013) and burned area (Balshi et al. 2009a). Both these modeling efforts using the Terrestrial Ecosystem Model (TEM) show changes in carbon cycling at large scales across the interior of Alaska (0.5° and 1° grid cells), but lack the detail that bottom-up approaches, such as the one used here, can provide. KH2012v1, and the refinements included in KH2012v2, use estimates of burned area and associated geospatial datasets at 60 m spatial resolution to make detailed assessments of burning within individual fire events – a level of detail unavailable in large scale modeling efforts. While both KH2012v1 and Genet et al. (2013) utilize field research from Turetsky et al. (2011b), the alterations made to KH2012v1 provide an important understanding of how changes in fire frequency are influencing boreal forest carbon emissions that have thus far not been addressed in large scale modeling.

Field studies have now begun to investigate burning in immature black spruce forests, and differences in the post-fire carbon storage and relative depth reduction have been found between immature and mature stands (Brown and Johnstone 2011, Hoy et al. in review-b). KH2012v2 was the first attempt to use these new data to better assess carbon consumption in immature black spruce stands. We found higher levels of carbon consumption compared to previous efforts, with changes due to including burning in the ground-layer of immature black spruce forests, a vegetation type not previously assessed. The carbon consumption reported in KH2012v2 is greater than that reported in KH2012v1 for 2004 (Table 4-5), and also greater than the 45.7 Tg of carbon consumption/emissions estimated by van der Werf et al. (2010), both of which did not assess burning in these immature spruce stands.

4.5 Conclusion

A better understanding of fire regime characteristics is still needed to increase understanding of how changes in fire frequency influence soil carbon pools and emissions, as well as vegetation patterns in the interior. Here we showed that accounting for immature black spruce forests previously classified as shrubs resulted in increases in the total carbon consumption. As the climate continues to warm (Hinzman et al. 2005), changes in fire frequency and severity could lead to shifts in vegetation, from post-fire recovery as black spruce forests to recovery as deciduous and even shrub dominated landscapes, resulting in a negative feedback on burned area (Johnstone and Kasischke

2005, Johnstone et al. 2010b, Johnstone et al. 2011, Mann et al. 2012, Kelly et al. 2013). This aspect of a changing fire regime is just recently emerging, and results from approaches such as KH2012v2 can help to better assess changes in the climate-fire-vegetation dynamics in interior Alaskan boreal forests, and to understand the impacts of these changes on carbon consumption and emissions.

Chapter 5: Conclusions, Implications and Next Steps

5.1 Principal Findings

The three studies presented within this doctoral research integrate geospatial/remote sensing and field datasets to address the research goal of investigating how an increase in fire frequency and a decrease in fire-free interval (FFI) influence soil organic layer carbon consumption during wildland fires (Chapter 1.2) and thus assess changes in carbon stocks in interior Alaskan boreal forests connected to increasing fire frequency.

In Chapter 2 of this dissertation, the relationship of burned area with FFI, vegetation, topography, and seasonal timing of burning was assessed. This research quantified burning within vegetated areas that had previously burned < 60 years ago in interior Alaska. It was found that approximately 20% of the burned areas in events between 2002 and 2008 were in short- to intermediate-FFI (S/I-I) regions and that the fraction of burned area (FBA) varied with FFI over time. A random forest analysis was used to assess the role of vegetation, topography, seasonality, and FFI in controlling variations in the FBA in these fire events. It was found that FFI, and to some degree vegetation type, had the strongest relationship with the FBA. These results indicated that it was fuel type and amount, not fuel condition, that were the dominant controls on fire behavior in these boreal regions of interior Alaska, and that changes in vegetation type associated with more frequent fire represent a negative feedback on burned area through alterations in the post-fire vegetation succession across the landscape.

In Chapter 3, a combination of field research and statistical analysis was used to assess depth of burn, residual soil organic layer depth, and soil carbon stocks within immature black spruce forests in interior Alaska. While depth of burn was similar between immature and mature black spruce field sites, relative depth reduction varied (with greater depth reduction in the immature stands) as less soil organic layer material was present in the ground-layer of these younger stands at the time of the disturbance. Carbon stocks varied between immature and mature stands, with less post-fire soil organic layer carbon stock in immature sites than mature sites (Table 3-5). These baseline measurements of post-fire organic layer depth, organic layer depth reduction, and post-fire carbon stock assessments in intermediate-FFI stands provided the data necessary to assess carbon consumption in immature black spruce forests. Such measurements will influence the understanding of post-fire succession and of modeling changes in carbon consumption due to increasing fire frequency.

In Chapter 4, refinements were made to a fire-related carbon emissions model used in interior Alaskan boreal forests in order to analyze the impacts of fuel loads and carbon consumption altered by a changing fire frequency. In this research changes were made to the existing model to account for black spruce forests in the early stages of recovery following fire disturbance (both through the creation of a new fuel type and the addition of new carbon consumption values for this new fuel type). This modeling effort resulted in increases in the total carbon consumption recorded for the two ultra-large fire years studied, with the increases due to additional carbon consumption in the ground-layer of burned recovering black spruce forests.

5.2 Discussion of Principal Findings

The boreal region of interior Alaska has seen numerous climate-related changes in precipitation, temperature, and ultimately the fire regime over the last few decades. The study of this region is important in creating baseline measurements and understanding ecosystem changes. While others have pointed to future increases in fire frequency and burned area associated with changing climate (Flannigan et al. 2005, Balshi et al. 2007, Balshi et al. 2009b), there have been no attempts to quantify the amount of current burning occurring in immature stands. The assessment of burned area within interior Alaska from 2002-2008 (presented in Chapter 2), represented an initial estimation of burning in recovering regions and showed that burning in these immature stands can be a substantial amount of total area burned (~20%). The research in Chapter 2 also showed the importance of fuel type and amount in understating patterns of burning across different vegetation types. And where others have noted the complex relationships between weather, fuels, and fire behavior in western subalpine (Agee 1997) or northern ecosystems (Hély et al. 2001), the detailed assessment here offers important insight into ecosystem dynamics in one particular northern ecosystem, the Alaskan boreal region. This dissertation research revealed that the FBA increased with increasing FFI, and indicated that it was FFI, and to some degree vegetation, that affected fire behavior in the S/I-I burned areas studied.

Burning in S/I-I stands could result in increases in burned area across the region. Permafrost thaw following fire events results in a thickening of the active layer (Johnson and Viereck 1983, Yoshikawa et al. 2002, Genet et al. 2013) and a drying of the surface organic layer, thus increasing the amount of organic soil available to burn during a subsequent fire event. Research from this dissertation has shown significant burning throughout the growing season in intermediate-interval black spruce burned sites (Table 3-2, Figure 3-7, Table 4-3). These sites, with increased vulnerability due to potential permafrost thaw and thick active layers, could sustain a second fire, with depth of burn similar to that from the initial fire event (*e.g.* see research presented in Chapter 3). However, this degree of burning would be unsustainable over additional burn cycles (assuming increased fire frequency) as the soil organic layer would become depleted over time.

Significant long-term negative feedbacks on burned area are also possible through changes in post-fire vegetation type (Johnstone et al. 2011, Mann et al. 2012, Kelly et al. 2013). Black spruce stand replacement has been found to be common only in low fire severity sites, with deciduous seedlings dominating recovery in high fire severity sites (Johnstone et al. 2010b). This trend has been found in short fire-free interval (short-FFI) black spruce stands as well, where recruitment was reduced in young stands as compared to long-FFI stands (Brown and Johnstone 2012). Using an extensive dataset of immature-FFI black spruce burned stands, the results presented in Chapter 3, showed that burning in these stands frequently results in small post-fire soil organic layer depths, with little to no soil organic material above the mineral soil. It is these stands that are particularly vulnerable to the post-fire vegetation shifts. And while increases in post-fire deciduous vegetation would result in increases to above-ground biomass, it is not clear that this above-ground increase would offset the fire-related losses of the below-ground carbon pool in the soil organic layer of black spruce forests and peatlands (Alexander et al. 2012).

Changes in climate and the fire regime are resulting in alterations to the carbon pools located in the thick soil organic layers of black spruce forests and peatland sites in the region (Turetsky et al. 2011). The research in Chapter 4 presented a first assessment of carbon consumption in immature black spruce stands within interior Alaska using a detailed (60 m spatial resolution) bottom-up modeling approach. Using immature black spruce carbon consumption values created based on the field research discussed in Chapter 3, overall carbon consumption was found to be higher for fire events from the two ultra-large fire years (2004 and 2005) compared to a previous approach which did not account for these immature forests (Kasischke and Hoy 2012). This new level of detailed information can be used to inform and validate process-based models such as TEM (see, *e.g.* the fire severity model using the dynamic organic soil layers of TEM in Genet et al. (2013)), which would result in more realistic assessments of the fire-climate-vegetation dynamics within the region and would result in improved modeling of soil carbon pools and emissions across the region as climate continues to change.

5.3 Future Research

There are multiple ecological processes occurring within this boreal region necessitating further research. Climate change has resulted in the compound disturbances of not only changes in the fire regime, but also changes in permafrost dynamics and post-fire vegetation succession. These ecosystem processes have important feedbacks to the fire and climate regimes of the region, as well as to the human societies located within this region (such as losses to infrastructure through permafrost degradation). There are a number of additional areas for research in terms of field measurements, remote sensing and geospatial analyses, and modeling studies that are discussed in the following sections (see summary in Table 5-1).

Table 5-1: Future research areas based on the doctoral research related to short- and intermediate- fire-free interval (S/I-I) issues from this dissertation.

Research Method	S/I-I Issue to Address	Potential Research
Field Research	Post-fire succession	Measure seedling recruitment in short- and intermediate- interval burned stands
	Permafrost degradation	Measure soil active layer depth and soil temperature following fire in short- and intermediate- interval black spruce stands
	Carbon cycling	Expand the depth of burn and post-fire depth measurements to include additional short- and intermediate- interval fire events
Remote sensing/Geospatial Analysis	Fraction of burned area	Utilize newly available dNBR datasets to determine FBA with greater accuracy for fire events from additional years (1984-2000, 2009-2011)
	Fire severity	Investigate methods to discriminate levels of fire severity in short- and intermediate- interval fire events
	Post-fire succession	Investigate methods to use multiple sources of remotely sensed imagery to map forest recovery in short-FFI stands
Modeling	Carbon cycling and consumption estimates	Expand the carbon consumption analysis from Chapter 4 to include additional fire years (adding small and large fire years to the analysis) Improve carbon consumption methods using theoretical, process-based models

5.3.1 Field Research

Future field research could address questions of post-fire succession, permafrost degradation and carbon cycling in short- to intermediate-interval (S/I-I) black spruce stands. While a number of studies reliant on field research have addressed post-fire succession in mature black spruce forests (Johnstone et al. 2004, Johnstone and Kasischke 2005, Johnstone et al. 2010b, Johnstone et al. 2011), few have addressed this issue in S/I-I stands (Johnstone and Chapin 2006, Brown and Johnstone 2012). Changes to vegetation patterns, from coniferous vegetation to deciduous and even shrub-dominated stands (Johnstone et al. 2010b, Mann et al. 2012), will influence long-term ecosystem structure and function.

Additionally, increased knowledge of active layer depth and soil temperature in recently burned S/I-I stands is needed to improve the understanding of permafrost degradation in these disturbed areas. Following fire, disturbed stands are at high risk for permafrost degradation due to the loss of the insulating soil organic layer above. Following S/I-I fire events, the post-fire residual layer is further depleted and the likelihood of additional permafrost degradation is heightened. Increased understanding of these processes is important to both permafrost and carbon cycling modeling efforts, and additional field research could be used to both influence and validate modeling efforts.

Field research could also be undertaken to expand the depth of burn and post-fire residual soil organic layer measurements in intermediate-interval black spruce stands. Due to difficulties accessing the remote locations within the boreal forests of

Alaska, the field research collected for this dissertation was confined to four intermediate-interval fire events located along the road network (Figure 3-1). Additional research could extend this collection of sites to include a greater number of plots within these four fire events, as well as investigate other potential S/I-I burned areas. Table 3-2 shows that measurements were not made of early-season burning in North-facing slopes or late-season burning in South-facing slopes, and additional field research could address these information gaps, assuming suitable burned areas could be found. Assessing above-ground biomass in these stands could also allow for better calculations of the carbon pools in these regrowing stands, similar to the assessments of Brown and Johnstone (2011). These proposed field studies in S/I-I stands will contribute to improved understanding of carbon cycling in this region, and could be used to validate remote sensing products and provide critical information for modeling efforts.

5.3.2 Remote Sensing/Geospatial Analysis

Areas of future research extend beyond field studies to include additional avenues of remote sensing and geospatial analysis. Since the completion of this dissertation research, additional dNBR datasets have become available for Alaska (from 1984-2000 and 2009-2011) from the Mapping Trends in Burn Severity Program (www.mtbs.gov). The fire perimeter analysis used in Chapter 2 could be supplemented with burned and unburned areas derived from this dNBR product to better represent the patchiness and spatial heterogeneity found within burned areas, thus providing improved estimates of fraction of burned area in S/I-I burned stands. Such estimates could reduce uncertainties in estimating carbon consumption.

Research could also extend the understanding on mapping of fire severity from mature black spruce burned stands (Barrett et al. 2010, Barrett et al. 2011) to investigate fire severity in S/I-I stands. In addition, research is needed to develop approaches to using remotely sensed datasets to map post-fire vegetation recovery. This capability would result in increased understanding of how a changing fire regime is impacting broad vegetation patterns across the landscape.

5.3.3 Modeling Efforts

The results from field studies and remote sensing analyses of fire regime changes in S/I-I burned stands could be used to further refine models of carbon cycling and carbon emissions in the interior Alaskan boreal region. The per pixel analysis performed in Chapter 4 was for two ultra-large fire years only (2004 and 2005); additional research could expand this dataset to include other fire years from the 2000s (such as small and large fire years).

Applying the results from Chapter 4 to process-based analyses, such as TEM, could also improve carbon consumption estimates within the boreal region. Genet et al. (2013) discussed the importance of understanding changing post-fire vegetation patterns in order to better model carbon dynamics. Others have noted that changes in above-ground carbon accumulation are likely in mid-succession stands if black spruce dominated stands shift to deciduous species (Alexander et al. 2012); however, the long-term carbon balance from these shifts is not yet know.

Finally, improved understanding of permafrost degradation due to S/I-I fire events would also aid modelers in better understanding perturbations to this system. Incorporating field research of active-layer depth and soil temperature in S/I-I burned stands could alter current knowledge of permafrost degradation and soil decomposition in these stands. Overall, incorporating more detailed information from S/I-I burned stands could aid efforts to better model and understand changes to this system with climate change.

5.4 Research and Policy Implications

Changes in the fire regime of interior Alaskan boreal forests have wide-reaching effects throughout the region, and even at national, international, and global scales (from changes in the ways local human populations interact with the land to the estimates of carbon pools and sources needed to understand carbon cycling throughout the earth system). Losses in boreal forest cover over the past decade, predominantly due to fire, are second only to tropical regions (Hansen et al. 2013). This conclusion comes in spite of an approach limiting ‘forests’ to be vegetated areas greater than 5 meters tall, not always the case in boreal forests (Hollingsworth et al. 2006). The release of carbon into the atmosphere, both through the combustion process as well as through the decomposition of soils recently made available due to permafrost thaw, results in a positive feedback further contributing to climate warming (Hayes et al. 2011). Better understanding landscapes impacted by more frequent fire (through field research, remote sensing and modeling analyses) can inform policy makers as they work to craft legislation relevant to the changing conditions in these boreal regions.

Northern systems provide numerous ecosystems services (see Collins et al. (2011) for a description of ecosystem services) to local communities, and extend even to the global society. Alterations to the fire regime can influence these services (such as loss of food resources, loss of infrastructure, and increased climate warming). Local land management agencies must balance the needs of local residents and the broader community of those accessing the resources contained within Northern ecosystems, and informed science can aid in this process. Scientific study of arctic and boreal regions has been identified as an important research priority here in the United States. The Interagency Arctic Research Policy Committee (IARPC), which receives its direction from the Executive Office of the President, has identified the investigation of the frequency and severity of wildland fires in the Arctic as a research priority (IARPC 2013). Additionally, the National Aeronautics and Space Administration (NASA) Terrestrial Ecology Program has recently begun planning for a major field and remote sensing campaign in the Arctic and Boreal regions of Alaska and Canada – the Arctic-Boreal Vulnerability Experiment (ABoVE, above.nasa.gov), and a scoping study has been funded by the NASA Ocean Biology and Biogeochemistry Program to investigate land-ocean interactions in the Arctic. Locally within Alaska, Landscape Conservation Cooperatives (LCCs) have been formed through partnerships with federal agencies, local governments, tribes, and other stakeholders to provide scientific tools and information to local land managers. The research presented in this dissertation is highly relevant in light of these efforts to continue research in arctic and boreal regions, and the additional research suggested in Table 5-1 could be completed within these arctic-boreal research campaigns.

List of Acronyms

ABoVE	Arctic-Boreal Vulnerability Experiment
AR	Adventitious Root
BD	Big Denver Fire Event
BS	Black Spruce (*Picea mariana*)
C	Carbon
CCSP	U.S. Climate Change Science Program
CFC	Crown Fuel Consumption
CGCM	Canadian Climate Center Coupled General Circulation Model
CK	Chicken Fire Event
CR	Cascaden Ridge Fire Event
CV	Coefficient of Variation
DC	Drought Code
dNBR	differenced Normalized Burn Ratio
DWDFC	Dead and Downed Woody Debris Fuel Consumption
EW	East-West
FBA	Fraction of Burned Area
FC	Fish Creek Fire Event
FFFC	Forest Floor Fuel Consumption
FFI	Fire-free interval
FL	Flat Lowland
FRI	Fire Return Interval
FU	Flat Upland
FWI	Fire Weather Index
HADCM	Hadley Centre Climate Model
IARPC	Interagency Arctic Research Policy Committee
II	Intermediate-interval or intermediate fire-free interval
KC	King Creek Fire Event
KH2012v1	Kasischke and Hoy (2012) Model Version 1
KH2012v2	Kasischke and Hoy (2012) Model Version 2
LCC	Landscape Conservation Cooperatives
LFDB	Alaskan Large Fire Database

LI	Long-interval or Long Fire-free Interval
LTER	Long Term Ecological Research
MODIS	Moderate Resolution Imaging Spectroradiometer
MSE	Mean Square Error
MTBS	Monitoring Trends in Burn Severity
N	North
NACP	North American Carbon Program
NASA	National Aeronautics and Space Administration
NED	National Elevation Dataset
NESSF	NASA Earth and Space Science Fellowship
NLCD	National Land Cover Dataset
S	South
SE	Standard Error
S/I-I	Short- to Intermediate-FFI or Short- to Intermediate- Fire-free interval
SI	Short-interval or short fire-free interval
SOC	Soil Organic Carbon
SOCCR	State of the Carbon Cycle Report
SOL	Soil Organic Layer
TEM	Terrestrial Ecosystem Model
UMD	University of Maryland

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