

SPATIAL AND TEMPORAL TRENDS IN VEGETATION INDEX IN
THE BONANZA CREEK EXPERIMENTAL FOREST

Presented to the Faculty
of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements

For the Degree of
MASTER OF SCIENCE

By

Rebecca A. Baird, B.S.

Fairbanks, Alaska

August 2011

Abstract

Climate has warmed substantially in boreal Alaska since the mid-1970s. The direct effects of rising temperatures on sub-Arctic ecosystems are already being observed in the form of drought stress, increased fire frequency and severity, and increased frequency and severity of herbivorous insect outbreaks. These effects of climate change are having a direct impact on the vegetation of the boreal forest and leading to a decreased remotely sensed normalized difference vegetation index (NDVI), which is an effective proxy for landscape-scale plant productivity and photosynthesis. Therefore, NDVI is a useful tool to examine landscape-scale changes in vegetation over time, especially in the context of known climate change. The overarching goal of my research was to assess the change in vegetation index at multiple scales over a period of 23 years at Bonanza Creek Experimental Forest. I used a combination of remote sensing and field sampling to examine trends in NDVI across landscape units, topographic classes, and plant communities.

My project consists of two main parts: 1) Create a floristically-based landcover classification through field sampling and incorporating the field data into a map using satellite imagery and 2) Examine trends in the vegetation index using 11 Landsat TM and ETM+ images from 1986-2009. By using Landsat imagery and doing a landcover classification of my study area I was able define trends in NDVI to specific landscape units, topographic classes, and plant communities in the study area.

Table of Contents

	Page
Signature Page	i
Title Page	ii
Abstract	iii
Table of Contents	iv
List of Figures	viii
List of Tables	x
Acknowledgements	xi
Chapter 1 General Introduction	1
<i>References</i>	5
Chapter 2 Vegetation Classification of the Bonanza Creek Experimental Forest	9
<i>Background</i>	9
<i>Methods</i>	11
<i>Field Methods</i>	11
<i>Vegetation Classification</i>	12
Ordination	12
Mapping	13
<i>Results</i>	14

<i>Uplands</i>	16
<i>Floodplains</i>	17
<i>Community Descriptions</i>	18
<i>Uplands</i>	20
Acidic Black Spruce <i>Picea mariana</i>	22
Aspen <i>Populus tremuloides</i>	22
Birch <i>Betula neolaskana</i>	23
Upland Mixed Forest	24
Upland White Spruce <i>Picea glauca</i>	25
<i>Floodplains</i>	26
Non-acidic Black Spruce <i>Picea mariana</i>	27
Balsam Poplar <i>Populus balsamifera</i>	27
Floodplain White Spruce <i>Picea glauca</i>	28
Floodplain Early Successional.....	29
Floodplain Mixed Forest.....	30
Disturbed Sites	30
<i>Conclusions</i>	31
<i>References</i>	33

Chapter 3 Assessment of Change in Vegetation Index in Bonanza Creek

Experimental Forest	38
<i>Abstract.....</i>	<i>38</i>
<i>Introduction.....</i>	<i>38</i>
<i>Methods</i>	<i>40</i>
<i>Study Area.....</i>	<i>40</i>
<i>Processing Landsat sensor data</i>	<i>43</i>
<i>Dividing the Bonanza Creek Experimental Forest landscape.....</i>	<i>46</i>
Results.....	49
<i>NDVI trends by study area and landscape position</i>	<i>49</i>
<i>NDVI trends by topographic class.....</i>	<i>52</i>
<i>Influence of wildfire.....</i>	<i>54</i>
<i>Influence of vegetation type.....</i>	<i>57</i>
Discussion.....	64
<i>Study Area NDVI Trends</i>	<i>65</i>
<i>Effect of landscape position on NDVI trends</i>	<i>65</i>
<i>Effects of topographic class on NDVI trends</i>	<i>67</i>
<i>NDVI following wildfire</i>	<i>68</i>

<i>Differences in NDVI between vegetation types</i>	<i>69</i>
<i>Addressing potential bias due to sensor degradation.....</i>	<i>71</i>
<i>References.....</i>	<i>72</i>
Chapter 4 General Conclusions.....	80
<i>References.....</i>	<i>82</i>

List of Figures

	Page
Figure 2.1 NMDS ordination of all BCEF relevé sites.....	15
Figure 2.2 NMDS ordination of the upland sites.....	17
Figure 2.3 NMDS ordination of Floodplains.....	18
Figure 2.4 Landscape units used for analysis	21
Figure 2.5 Acidic black spruce stand.....	22
Figure 2.6 Aspen stand	23
Figure 2.7 Birch stand.....	24
Figure 2.8 Upland mixed forest stand.....	25
Figure 2.9 Upland white spruce stand.....	26
Figure 2.10 Non-acidic black spruce	27
Figure 2.11 Balsam poplar stand	28
Figure 2.12 Floodplain white spruce stand.....	29
Figure 2.13 Floodplain early successional community.....	30
Figure 3.1 Landscape units used for analysis	42
Figure 3.2 Mean daily MODIS NDVI values for 2008 within Path70 Row15 Landsat scene area, illustrating peak seasonal green up. Daily NDVI variations in this time series are likely due to variation in vegetation type (broadleaf and coniferous composition) in each cloud-screened daily mean NDVI.	45

Figure 3.3 1986-2009 trend in mean NDVI value by landscape position within the study area (excluding burned pixels) (n=11 years).	51
Figure 3.4 1986-2009 trend in mean NDVI value for unburned upland south and north facing slopes within the study area (n=11 years).....	53
Figure 3.5 1986-2009 trend in mean NDVI value the 1983 Rosie Creek burn area and the 2001 Survey Line burn area (n=11 years).....	55
Figure 3.6 1986-2009 trend in mean NDVI value from the 1983 Rosie Creek burn and the unburned uplands (n=11 years).....	56
Figure 3.7 1986-2009 trend in Mean NDVI value from the 2001 Survey Line burn area and the unburned lowlands (n=11 years).....	57
Figure 3.8 1986-2009 trend in Mean NDVI value for upland and floodplain white spruce (n=11 years).	60
Figure 3.9 1986-2009 trend in Mean NDVI value for aspen forests: (a) all dates included (n=11 years) and (b) high defoliator insect year scenes excluded (aspen leaf tortrix in 1986 and aspen leaf miner in 2006) (n=9 years).....	61
Figure 3.10 1986-2009 trend in Mean NDVI value for upland deciduous (birch) conifer (white spruce) (n=11 years).	62
Figure 3.11 Residuals for selected vegetation types from 2006 following the 2004 drought	63
Figure 3.12 Total growing season (May-August) precipitation for the Fairbanks Airport.	67

List of Tables

	Page
Table 2.1 Kendall correlations of environmental variables and site characteristics.....	16
Table 2.2 Area in hectares of each community type.....	19
Table 3.1 Landsat scenes used for analysis. Images with cloud cover were masked to eliminate cloud effects on NDVI analysis.	44
Table 3.2 Vegetation classes used for analysis of NDVI trends.....	49
Table 3.3 1986-2009 mean NDVI linear regression trends by subsample area (n= 11 years).....	50
Table 3.4 Correlation matrix of annual residuals for 1986-2009 trend in mean NDVI value by landscape position within the study area (excluding burned pixels) (n=11 years).	52
Table 3.5 Correlation matrix of annual residuals for 1986-2009 trend in mean NDVI value by slope class within the study area (excluding burned pixels) (n=11 years).....	54
Table 3.6 1986-2009 mean NDVI linear regression trends by vegetation class subsample area (n= 11 years).....	59
Table 3.7 Correlation matrix of annual residuals for 1986-2009 trend in mean NDVI value by vegetation class within the study area (excluding burned pixels) (n=11 years).	62
Table 3.8 1986-2009 trend in mean NDVI value by for individual polygons by vegetation class within the study area (p-value < 0.01) (excluding burned pixels) (n=11 years).	64

Acknowledgements

I would like to thank my committee co-chairs, Dr. Teresa Nettleton Hollingsworth and Dr. David Verbyla, for their unconditional support, patience, and understanding. They both provided valuable guidance throughout the research and patiently reviewed many drafts of the thesis.

I was fortunate to have two very well qualified field assistants over the two summers of field work I conducted. Becky Hewitt provided a great deal of help and laughter for my first summer and Sally Andersen, along with the occasional company of her two sons, was a wonderful and knowledgeable companion during my second summer of field work.

My family here in Alaska and farther afield has provided support and encouragement throughout this study. I'd like to give special acknowledgement to my husband Cameron Baird for his steady support, patience, and encouragement. Thank you to my in-laws Linda Unsicker and Dr. Carl Unsicker for their encouragement and for helping to ease the burden of everyday tasks. Unfortunately Dr. Carl Unsicker passed away suddenly and was not able to see the completion of this research.

I would like to thank my current employer ABR Inc., Environmental Research and Services for allowing me the time and space to finish my thesis. Janet Kidd, an employee of ABR Inc. and my third committee member, provided valuable input throughout the research.

Several other people have provided support, guidance, and ideas throughout my research. Tako Reynolds' input was crucial for the vegetation mapping portion of my research. Dana Nossov provided some early and constructive feedback on my thesis. Jamie Hollingsworth and Brian Charlton helped in many ways including getting me to my river accessed field sites. Glenn Juday provided great insight into the trends I observed. Ellen Trainor patiently instructed me in the use of the pH meter in the SNRAS soils lab.

Funding for this research was provided by the Bonanza Creek LTER program (funded jointly by NSF award DEB-0620579 and USDA Forest Service, Pacific Northwest Research Station grant RJVA-PNW-01-JV-11261952-231 and by a University of Alaska Fairbanks (UAF) Center for Global Change Student Award. The UAF School of Natural Resources and Agricultural Sciences also supported this research by providing teaching assistantships.

Chapter 1 General Introduction

The boreal forest is the second largest terrestrial biome (Whittaker, 1975) and occupies approximately 65% of land in Alaska (Van Cleve et al., 1983a). Much of the boreal forest in Alaska is located in the interior region, north of the Alaska Range and south of the Brooks Range.

Vascular plant diversity in interior Alaska is relatively low and vegetation is distributed in a mosaic determined largely by time since disturbance (typically fire or flooding), site drainage (typically related to topography and parent material), and topographically affected microclimate (Chapin et al., 2006). In interior Alaska, tree canopies are dominated by white spruce, black spruce, quaking aspen, Alaskan birch, and balsam poplar. The sun angle is low in interior Alaska, due to latitudes exceeding 60° north. This low sun angle leads to dramatic differences in the amount of direct sunlight hitting south facing vs. north facing slopes. The difference in sunlight leads to differences in growing season length, snow depth, the presence of permafrost, and variation in plant communities. In addition to aspect, slope or landscape position plays an important role in the distribution of vegetation due to effects on drainage, water availability, permafrost development, and type and severity of disturbance.

The global climate is warming and northern latitudes are experiencing amplified warming (Wendler et al., 2009). In addition, changes in ocean climate due to the Pacific Decadal Oscillation have led to shifts in disturbance regimes (Duffy et al. 2005). For example, mean annual temperature in the Fairbanks area, in interior Alaska, has risen

1.4° C, over the past century, while the worldwide increase has been 0.8° C. These climate trends are affecting vegetation distribution in the interior Alaska boreal forest directly through changes in fire frequency and severity (Duffy et al., 2005; Johnstone et al., 2010) and indirectly through changes in phenology (Soja et al., 2007). There have also been observed changes in vegetation productivity due to drought stress (Barber et al., 2000), increased insect infestation (Volney et al., 2000), and longer growing seasons (Wendler et al., 2009). Most of these changes have led to decreases in vegetation productivity as measured through eddy covariance (Kljun et al., 2006), tree ring data (Barber et al., 2000), and remotely sensed vegetation indices (Llyod et al., 2007; Parent et al., 2010; Verbyla, 2008).

In addition, one would predict that changes in climate will have a large effect on plant community composition (Euskirchen et al., 2010). Therefore it is critical to gain a better understanding of the current state of vegetation in interior Alaska and how vegetation may be responding to climate change related stress. My work provides an accurate floristic classification of the current vegetation in the Bonanza Creek Experimental Forest (BCEF) and explores temporal trends in the response of vegetation to climate change related stress.

The first component of my research was to develop a floristic-based classification of the study site and a polygon based map of the plant communities. A floristic classification takes into account all the species in a plant community, and provides the basis for a better understanding of species interactions with each other and the

environment (Westhoff et al., 1978). My classification provides baseline information on the composition of plant communities in the study site. I was able to use the vegetation classification to examine trends in a remotely sensed vegetation index (NDVI), which is a strong proxy for vegetation productivity (Pettorelli et al., 2005).

Most boreal NDVI studies have been on a regional scale (Bunn et al., 2007; Goetz et al, 2005; Verbyla, 2008). My study is one of the first to take a closer examination of known regional declining NDVI trends by linking remotely sensed data to plot level vegetation data. To do this I focused on a relatively small study site, the Bonanza Creek Experimental Forest (BCEF). BCEF occupies approximately 5,000 hectares of boreal forest land 20 km southwest of Fairbanks, Alaska. There has been ongoing ecological research at BCEF since the establishment in 1963.

This thesis is organized into two main chapters. The first chapter describes the process of creating a floristic classification of plant communities in BCEF and using that classification to produce a polygon based vegetation map of the study area. This is the first vegetation map produced for BCEF since 1992 and the first floristic-based classification. It not only provides the scientific community with a current vegetation map and serves as a base map for studying future vegetation change in BCEF, but it acts as a first step for creating floristic-based vegetation maps across interior Alaska.

The second chapter uses NDVI to examine changes in vegetation greenness. In particular, I was interested in disentangling the observed changes in NDVI based on

landscape position, topographic position, and by vegetation type using the vegetation map I produced.

The overall goal of this work was to provide an in depth examination of the known regional “browning” trend on a more local-scale. Due to the small-scale and high-resolution of my remotely sensed data and my field sampling I was able to create a bridge between remotely sensed data and what is actually happening at the plant community level. This research provides baseline data for the study area, BCEF, and provides a relatively easy and inexpensive method for monitoring of landscape changes that result from climate, fire, or other influences that may affect the resiliency of plant communities. By beginning the process of assessing trends in NDVI at BCEF all the tools are in place to ease continued monitoring of trends. This research will also benefit researchers at BCEF who are interested in landscape ecology and wildlife habitat.

References

- Barber, Valerie A., Juday, Glenn Patrick, and Finney, Bruce P. 2000. "Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress." *Nature* no. 405 (6787):668.
- Beck, P. S.A., Juday, G., Alix, C., Barber, V., Winslow, S., Sousa, E., Heiser, P., Herriges, J.D., and Goetz, S.J. 2011. "Changes in forest productivity across Alaska consistent with biome shift." *Ecology Letters* no. 14 (4):373-379.
- Bunn, A.G., Goetz, S.J., Kimball, J.S., and Zhang, K. 2007. "Northern high-latitude ecosystems respond to climate change." *EOS* no. 88 (34).
- Chapin, F. S., III, Oswood, M. W., Van Cleve, K., Viereck, L. A., and Verbyla, D. L. 2006. "Alaska's Changing Boreal Forest."
- Duffy, Paul A., Walsh, J. E., Graham, J.M., Mann, D.M., and Rupp, S. T. 2005. "Impacts of large-scale atmospheric-ocean variability on Alaskan fire season severity." *Ecological Applications* no. 15 (4):1317-1330.
- Euskirchen, E.S., McGuire, A. D., Chapin III, F.S., and Rupp, S. 2010. "The changing effects of Alaska's boreal forests on the climate system." *Canadian Journal of Forest Research* no. 40:1336-1346.
- Goetz, Scott J., Bunn, Andrew G., Fiske, Gregory J., and Houghton, R.A. 2005. "Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance." *PNAS* no. 102 (38):13521-13525.

- Johnstone, J.F., Chapin III, F. S., Hollingsworth, T.N., Mack, M.C., Romanovsky, V.E., and Turetsky, M.R. 2010. "Fire, climate change, and forest resilience in interior Alaska." *Canadian Journal of Forest Research* no. 40:1302-1312.
- Kljun, N., Black, T., Griffis, T., Barr, A., Gaumont-Guay, D., Morgenstern, K., McCaughey, J., and Nestic, Z. 2006. "Response of Net Ecosystem Productivity of Three Boreal Forest Stands to Drought." *Ecosystems* no. 9 (7):1128.
- Lloyd, A.H., and Bunn, A.G. 2007. "Responses of the circumpolar boreal forest to 20th century climate variability." *Environmental Research Letters* no. 2:1-13.
- McGuire, A. D., Ruess, R.W., Lloyd, A.H., Yarie, J., Clein, J., and Juday, G. 2010. "Vulnerability of white spruce tree growth in interior Alaska in response to climate variability: dendrochronological, demographic, and experimental perspectives." *Canadian Journal of Forest Research* no. 40:1197-1209.
- Parent, M.B., and Verbyla, D. 2010. "The browning of Alaska's boreal forest." *Remote Sensing* no. 2:2729-2747.
- Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.M., Tucker, C.J., and Stenseth, N. C. 2005. "Using the satellite-derived NDVI to assess ecological responses to environmental change." *Trends in Ecology and Evolution* no. 20 (9):503-510.
- Shulski, M.E., and Wendler, G. 2007. *The climate of Alaska*. Fairbanks: University of Alaska Press.
- Soja, Amber J., Tchebakova, Nadezda M., French, Nancy H. F., Flannigan, Michael D., Shugart, Herman H., Stocks, Brian J., Sukhinin, Anatoly I., Parfenova, E. I.,

- Chapin III, F. Stuart, and Stackhouse, Paul W Jr. 2007. "Climate-induced boreal forest change: Predictions versus current observations." *Global and Planetary Change* no. 56 (3-4):274.
- Van Cleve, K., and Dyrness, C.T. 1983. "Conclusions and directions for future research in taiga forest ecosystems." *Canadian Journal of Forest Research* no. 13:914-916.
- Van Cleve, K., Oliver, L., Schlentner, R., Viereck, L. A., and Dyrness, C.T. 1983. "Productivity and nutrient cycling in taiga forest ecosystems." *Canadian Journal of Forest Research* no. 13:747-766.
- Verbyla, D. 2008. "The greening and browning of Alaska based on 1982-2003 data." *Global Ecology and Biogeography* no. 17:547-555.
- Volney, W. Jan A., and Fleming, Richard A. 2000. "Climate change and impacts of boreal forest insects." *Agriculture, Ecosystems & Environment* no. 82 (1-3):283.
- Wendler, Gerd, and Shulski, Martha. 2009. "A Century of Climate Change for Fairbanks, Alaska." *Arctic* no. 62 (3):295.
- Westhoff, V., and van der Maarel, E. 1978. "The Braun-Blanquet approach." In *Classification of Plant Communities*, edited by Whittaker and R.H., 289-399.
- Whittaker, R.H. 1975. *Communities and ecosystems*. New York: Macmillan.
- Wilmking, Martin, Juday, Glenn P., Barber, Valerie A., and Zald, Harold S. J. 2004. "Recent climate warming forces contrasting growth responses of white spruce at treeline in Alaska through temperature thresholds." *Global Change Biology* no. 10 (10):1724-1736. doi: doi:10.1111/j.1365-2486.2004.00826.x.

Yarie, J., and Van Cleve, K. 2010. "Long-term monitoring of climatic and nutritional effects on tree growth in interior Alaska." *Canadian Journal of Forest Research* no. 40:1325-1335.

Chapter 2 Vegetation Classification of the Bonanza Creek Experimental Forest

Background

This map (appendix) is intended to support research at the Bonanza Creek Experimental Forest (BCEF), the only experimental forest located in the boreal region. BCEF was established in 1963 and is one of two sites for the Bonanza Creek Long Term Ecological Research program. BCEF is managed by the Boreal Ecology Cooperative Research Unit (BECRU), the northernmost outpost of the USDA Forest Service's Pacific Northwest Research Station (PNW). BCEF has been the focus of ongoing research to support a number of scientific studies involving: vegetation, soils, climate monitoring, mammals, and insects.

Despite the wide variety of disciplines involved in studies at BCEF most of the research focuses on vegetation either directly or indirectly. Research efforts have included studies of primary succession on the Tanana River floodplain (Van Cleve et al., 1993), the structure and function of taiga ecosystems (Van Cleve et al., 1983), and moose herbivory (Kielland et al., 1997). Because vegetation is an integral part of the majority of research at BCEF, it is imperative that researchers have access to detailed information on the abundance and distribution of plant communities within the research area.

The last vegetation map of BCEF was completed in 1992 (Yarie, 1992) and was classified to level four of the Alaska Vegetation Classification (Vioreck et al., 1992). This life form based classification system focuses on the canopy coverage and structural characteristics of the dominant tree, shrub, and herbaceous species. The vegetation

classes used in the 1992 vegetation map were: 1) balsam poplar; 2) balsam poplar – white spruce; 3) aspen; 4) paper birch; 5) paper birch – aspen; 6) white spruce; 7) white spruce: birch, aspen, birch – aspen; 8) black spruce; 9) black spruce dominated mixtures; and 10) alder, alder – willow. The map prepared for this study uses a floristic rather than life form approach for classifying the plant communities that occur in BCEF. A floristic classification takes into account all the species in a plant community, and provides the basis for a better understanding of species interactions with each other and the environment (Westhoff et al., 1978). It is widely accepted that in the boreal forest, plant community composition is important when considering many aspects of the ecosystem including: nutrient cycling, response to global change and disturbance, and response and control of ecosystem function (Bernhardt et al., 2011; Hollingsworth et al., 2006; McGuire et al., 2002; Schickhoff et al., 2002; Van Cleve et al., 1983; Walker et al., 1994; Westhoff et al., 1978).

The effects of a warming climate have already been observed in the boreal forest (Chapin et al., 2010) and plant community composition is predicted to change in interior Alaska in response (Euskirchen et al., 2009). Thus it is critical we gain a better understanding of plant community composition in the boreal forest and the environmental factors driving community structure and function. Having a clear understanding of the current state of plant community composition, particularly in an area such as BCEF, with long-term research programs, is important for assessing changes in community composition that may occur over time.

Methods

Field Methods

Field sampling took place in the summers of 2008 and 2009. Prior to sampling I conducted a reconnaissance level assessment of the study area by examining of aerial photos and conducting a field survey. Eighty-five sites were selected for sampling following criteria outlined in Mueller-Dombois et al. (1974) including: size of the stand; uniformity of the habitat within the stand; homogeneity of the plant cover; and access. Sampling at each of the 85 sites was done using the Braun-Blanquet relevé method, an internationally recognized method for collecting vegetation data for classification (Hollingsworth et al., 2006). The Braun-Blanquet method is a floristic approach to vegetation classification where the full species composition of a plant community drives the classification (Westhoff et al., 1978).

Once a site was selected, we flagged the center and measured to a 200 m² rectangular plot, which is the minimum recommended plot size for forest sampling including sampling of the tree stratum (Mueller-Dombois et al., 1974). All vascular, bryophyte, and lichen species were inventoried and assigned a Braun-Blanquet cover class based on a visual estimate of percent cover (Mueller-Dombois et al., 1974).

Nomenclature for vascular species followed Hultén (1968) and for non-vascular species Vitt et al.(1988).

Environmental factors such as topography, soil characteristics, and stand information were estimated at each plot. Coordinates and elevation were estimated using

a Trimble GeoExplorer 3 global positioning unit (Trimble Navigation Limited), slope and aspect were measured using an inclinometer and compass. Parent material, site contour, site moisture, and topographic position were determined based on visual inspection and prior knowledge of the study area. The age of oldest trees in the stand was estimated within ranges of years: 1) less than 30 years, 2) 30-60 years, 3) 61-80 years, 4) 81-120 years, and 5) > 120 years. These estimates were based on comparisons between the stand and data from Bonanza Creek LTER long-term vegetation plots. Finally, level and type of disturbance (moose, hare, and fire) was estimated through use of scalars. For moose and hare disturbance the levels recorded ranged from no sign present to more than 40% browse. For fire disturbance the range recorded was from no sign present to major signs of recent fire. We dug one soil pit at each site and measured depth of the organic layer and collected one mineral soil sample 10 cm below the mineral organic horizon to determine pH. Soil pH was measured in the laboratory using a Corning pH meter 140 (Corning Incorporated).

Vegetation Classification

Ordination

To determine the species composition for each map class I conducted ordinations of the 85 plots and 112 species using nonmetric multidimensional scaling (NMDS) and the program PC-ORD Version 5.0, from MjM Software (McCune et al., 1999). NMDS was chosen due to several advantages that it has over other ordination methods: it performs well with data that are non-normal; there is no assumption of linear correlations

among variables; and the ordination is based on biologically meaningful factors (Clarke et al., 1993; McCune et al., 2002). A preliminary ordination was done in each case to determine the appropriate number of axes using a Monte Carlo test, which determines if NMDS is extracting stronger axes than expected by chance. Once the appropriate number of axes was determined using a Monte Carlo test a final ordination was run using the best starting configuration as determined in the preliminary ordination. The map legend was developed based on distinct groups from the ordination and the black spruce classes (acidic and non-acidic) were based on the floristic classification done by (Hollingsworth et al., 2006).

Mapping

The primary base map was a color infrared QuickBird image provided by DigitalGlobe, Incorporated (Longmont, CO). The image was a mosaic of two scenes acquired on August 9, 2007 and June 18, 2007. The QuickBird imagery was delivered in the ortho-ready format and orthorectified using the rational polynomial coefficient orthorectification function in ENVI. A false color infrared SPOT image acquired on May 30, 2003 with a ground resolution of 4 meters and an ortho Lidar image from July 22, 2005, ground resolution of 0.375 meters, provided by AeroMetrics (formerly AeroMap US Anchorage, AK) were also used. I used the North American Datum of 1983 geodetic model and the Universal Transverse Mercator Zone 6 grid coordinate system for all imagery and the final map.

The final vegetation map is in the scale of 1:50,000. A minimum mapping unit of 0.07 hectares was selected; mapping was done at the 1:12,500 scale using ArcMap (Stohlgren et al., 1997). The map legend of 17 cover classes was developed based on the above mentioned NMDS ordinations. See pocket for the **Vegetation Map of the Bonanza Creek Experimental Forest**.

Results

A three dimensional ordination captured 71% of the variance in species composition at all 85 sites. The initial ordination of all 85 sites led to a division based on landscape unit (Figure 2.1). Due to this clear division between landscape units, I performed two subsequent ordinations on all sites in the uplands and in the floodplain. Access by road or river was sparse in the lowlands so there were only five lowland sites. The environmental variables most strongly correlated with the axes were: slope, aspect, elevation, and site moisture (Figure 2.1 and Table 2.1).

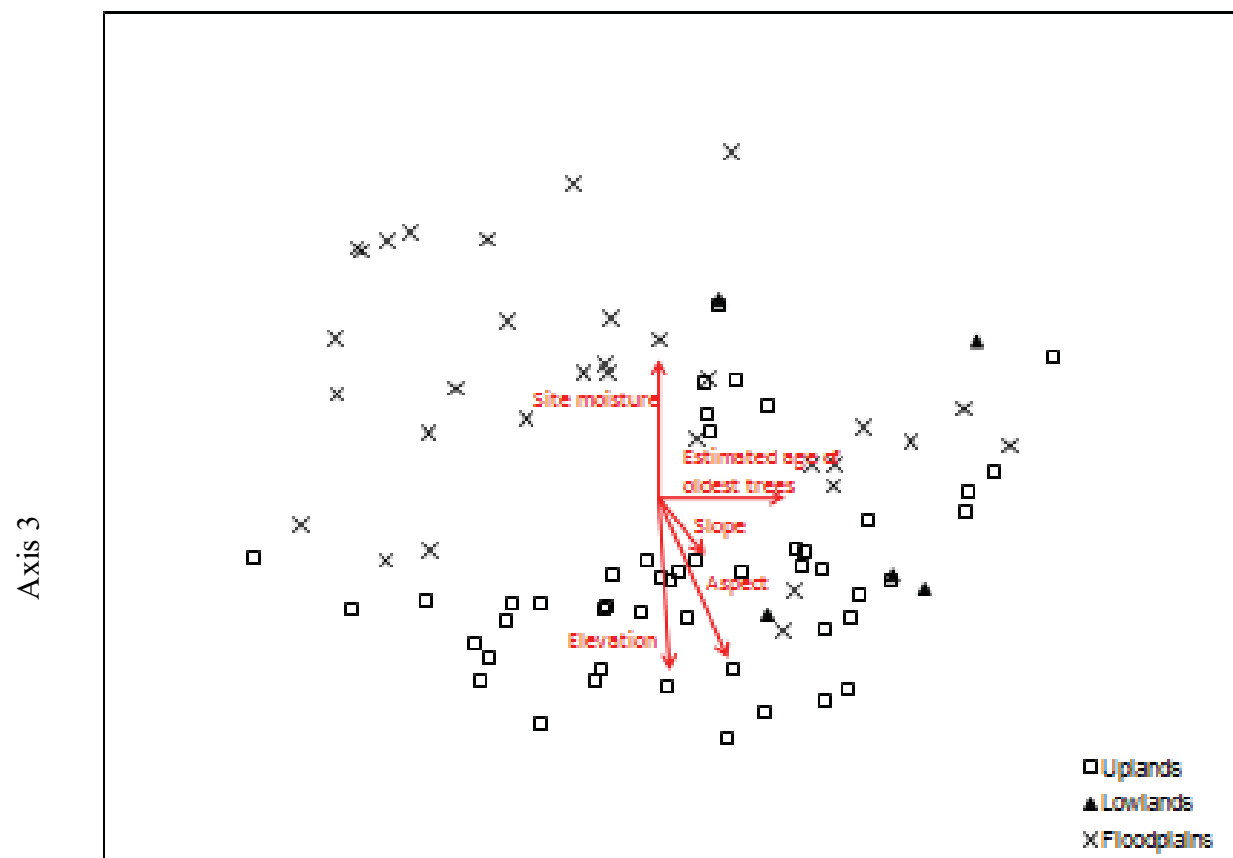


Figure 2.1 NMDS ordination of all BCEF relevé sites.

Axis 2

Table 2.1 Kendall correlations of environmental variables and site characteristics

Environmental variable	All Plots			Uplands			Floodplain		
	Axis 1	Axis 2	Axis 3	Axis 1	Axis 2	Axis 3	Axis 1	Axis 2	Axis 3
	tau	tau	tau	tau	tau	tau	tau	tau	tau
Slope	0.024	0.191	-0.484	-0.247	0.149	0.053	0.153	0.250	-0.105
Aspect	-0.133	0.232	-0.461	-0.010	-0.152	0.268	0.153	0.250	-0.105
Elevation	-0.034	0.150	-0.437	-0.290	-0.020	0.130	0.047	0.068	-0.010
Site moisture	-0.079	0.079	0.447	0.361	0.102	0.250	-0.050	0.015	0.000
Estimated age of oldest trees	-0.040	0.412	0.064	0.146	0.115	0.229	0.075	0.348	-0.382

Note: Values in bold met the criterion for significance $r^2 > 0.200$.

Uplands

A three dimensional ordination captured 79% of the variance in species composition in the upland sites. The uplands ordination led to six cover classes: acidic black spruce, birch forest, white spruce forest, mixed forest, aspen forest, and disturbed fire (Figure 2.2). Site moisture was the only environmental variable that was significantly correlated with the axes (Table 2.1) and site moisture was highest in the acidic black spruce forest (Figure 2.2). The acidic black spruce community stood out in the ordination space as the most distinctive community type in the uplands but the other six community types separated out well (Figure 2.2).

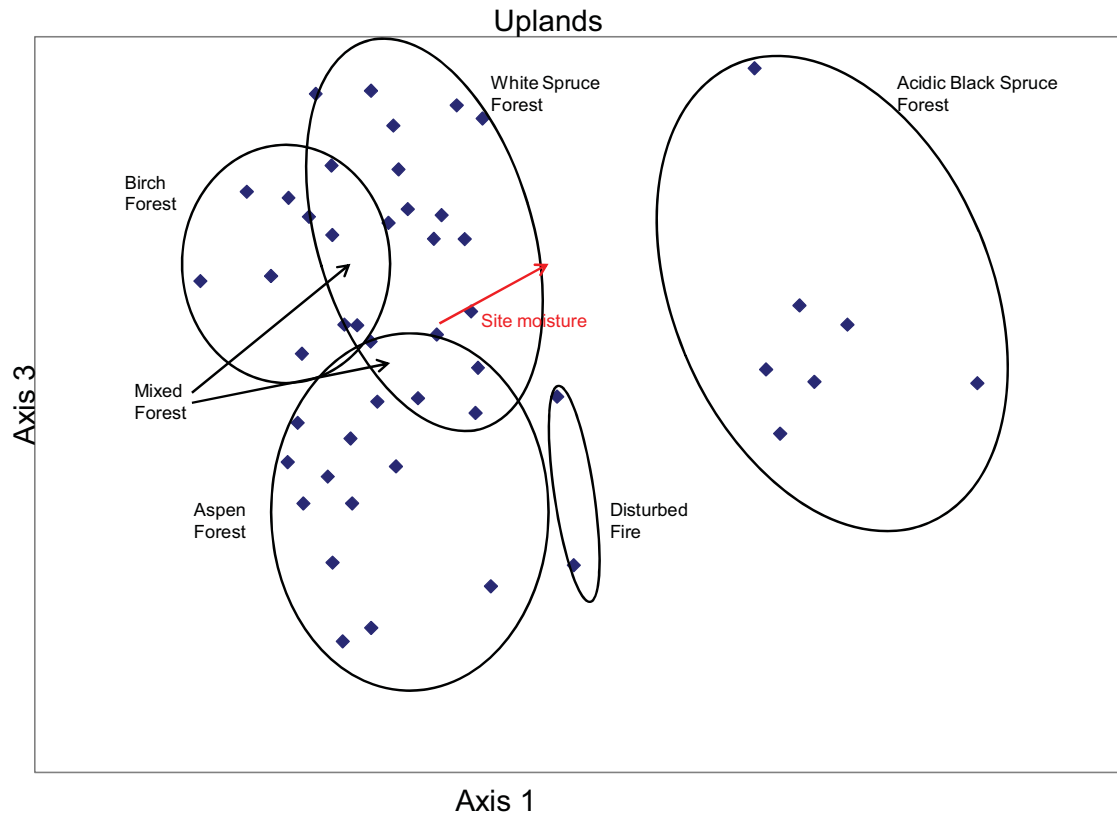


Figure 2.2 NMDS ordination of the upland sites

Floodplains

A three dimensional ordination captured 77% of the variance in species composition in the floodplain sites. The floodplains ordination led to seven cover classes: early successional, disturbed fire, non-acidic black spruce, deciduous forest, mixed forest, white spruce forest, and disturbed clear cut (Figure 2.3). Estimated age of oldest trees was the only environmental variable that was significantly correlated with the axes (Table 2.1) and the estimated age of oldest trees delineates a clear successional

progression in the ordination space (Figure 2.3). All community types in the floodplain were distinct in their ordination space, with early successional and recently burned communities being the most distinct (Figure 2.3).

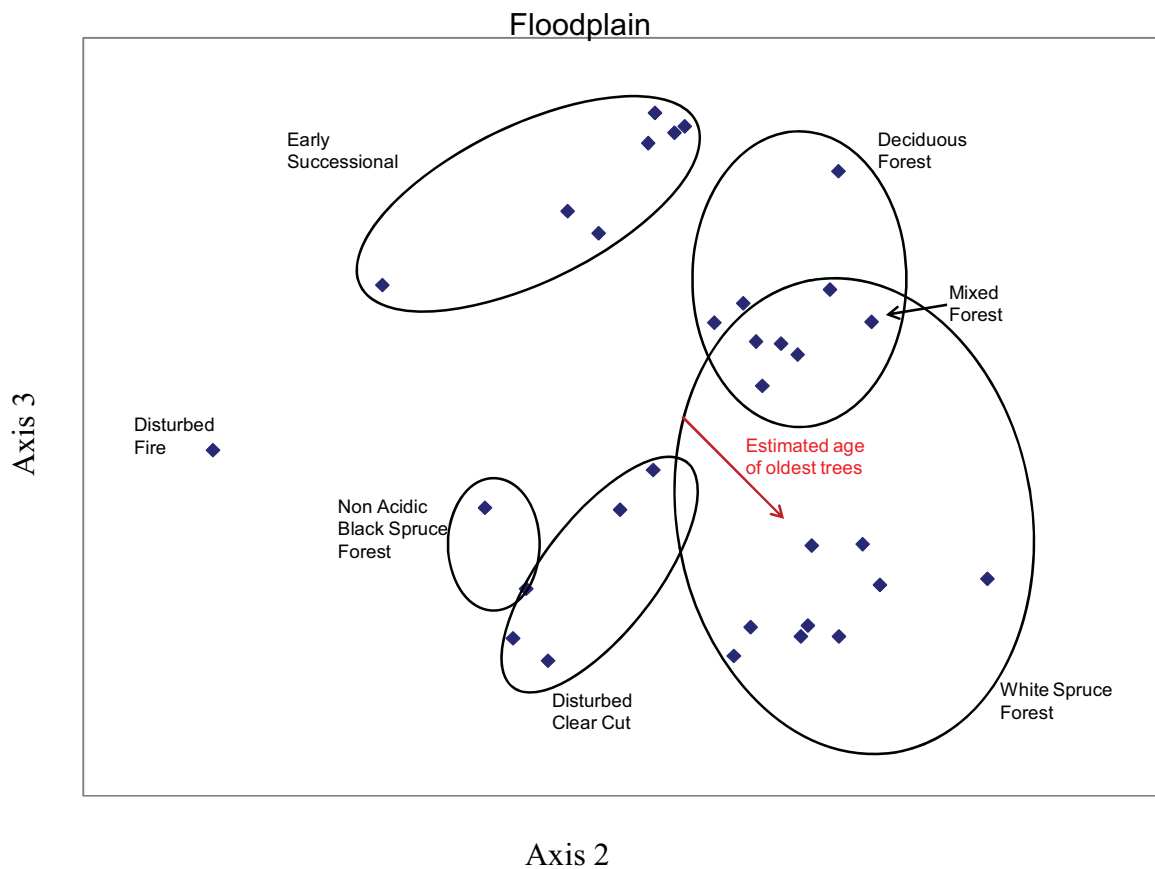


Figure 2.3 NMDS ordination of Floodplains

Community Descriptions

The sites were ultimately divided into 13 plant communities, six communities in the uplands and seven in the floodplain. The plant communities are described in detail in

the following section. Most of the study area was either a coniferous vegetation type or had been burned since 1983 and was classified as disturbed fire (Table 2.2).

Table 2.2 Area in hectares of each community type.

Stand Type	Area (hectares)
Upland Mixed Forest	2783
Disturbed Fire	1986
Acidic Black Spruce	1357
Floodplain White Spruce	1261
Non-acidic Black Spruce	1202
Upland White Spruce	688
Floodplain Early Successional	678
Open Wetland	540
Disturbed Clear-Cut	483
Birch	438
Aspen	345
Floodplain Mixed Forest	293
Balsam Poplar	280

Uplands

The uplands of BCEF extend from the area adjacent to the active floodplain of the Tanana River at approximately 120 m elevation to ridge tops at 470 m (Figure 2.4). The distribution of vegetation in the uplands is driven largely by: topographically controlled microclimate, and time since disturbance (Van Cleve et al., 1996). Aspect is particularly important at high latitudes due to the low sun-angle with north-facing slopes tending to receive less direct light and be cooler with a deeper snow pack, shallower rooting depth, and shorter growing season than south facing slopes (Van Cleve et al., 1996). Elevation influences the landscape in various ways, such as depth to water table, temperature, and wind exposure. Plant communities at lower elevations are typically closer to the water table, have warmer temperatures during the growing season, and are better protected from the wind. Fire is the dominant disturbance throughout interior Alaska boreal forest uplands (Van Cleve et al., 1996) and depending on fire-severity and pre-fire site conditions fires lead either to stand replacement or a series of successional stages (Johnstone et al., 2005 and 2010).

The uplands in the study area are underlain by schist and the soils are primarily silt-loam derived from loess deposits that originated from the Tanana River (Chapin et al., 2006). Although interior Alaska is within the zone of discontinuous permafrost north-facing upland slopes in late successional stages are likely to be underlain by permafrost (Van Cleve et al., 1996).

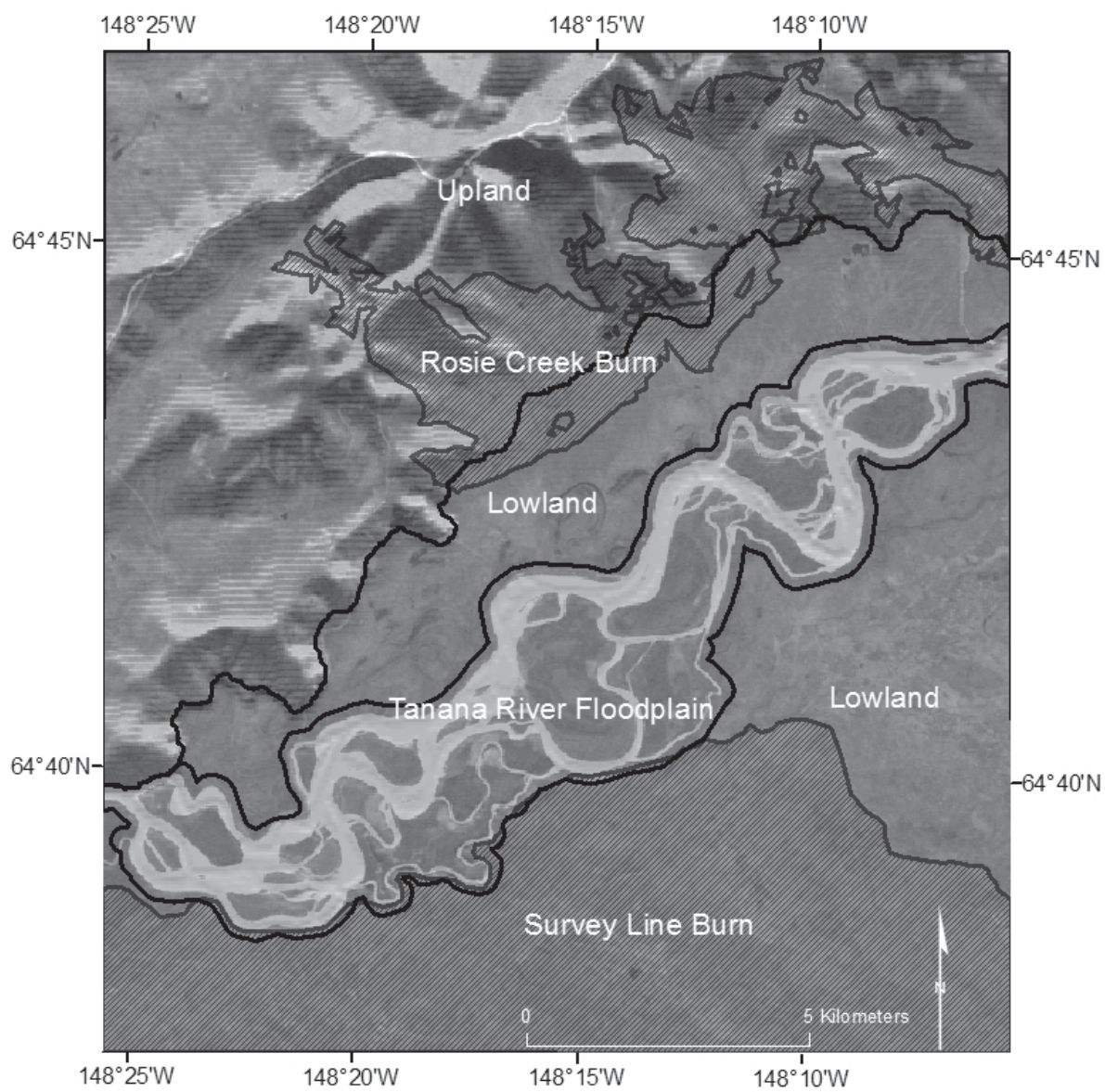


Figure 2.4 Landscape units used for analysis

Acidic Black Spruce *Picea mariana*

Acidic black spruce stands were found mainly in the uplands, especially in upland valley bottoms and steep north facing slopes, and in a few lowland sites with poor drainage. This vegetation class is typically underlain by permafrost. Acidic black spruce is second only to the upland mixed forests in extent of coverage for the non-disturbance cover classes (Table 2.2). Species that commonly occur in the acidic black spruce stands are: *Ledum decumbens*, *Spirea beauverdiana*, *Vaccinium vitis-idea*, *Cetraria islandica*, and *Sphagnum sp.* See (Hollingsworth et al., 2006) for a complete description of acidic black spruce communities.



Figure 2.5 Acidic black spruce stand

Aspen *Populus tremuloides*

Aspen stands occur mostly on dry, south-facing upland slopes. In stands of aspen with a closed canopy there tends to be very little aspen recruitment, instead the tree species with the highest recruitment was white spruce. Recent and extensive infestations of aspen leaf miner have occurred in BCEF (Werner, 2010), and these leaf-miner affected

stands of aspen are easy to discern on the high resolution QuickBird imagery (Coops et al., 2006; Smart, 2008). Other species that commonly occur in Aspen forests include:

Linnaea borealis, *Picea glauca*, and *Shepherdia Canadensis*.



Figure 2.6 Aspen stand

Birch *Betula nealaskana*

Birch stands occur mostly on relatively cool, moist north and east-facing slopes. As with closed canopy stands of aspen there tended to be little recruitment of birch and relatively high white spruce recruitment. Other species that commonly occur in birch forests include: *Cornus canadensis*, *Picea glauca* , *Viburnum edulé*, and *Lycopodium sp.*



Figure 2.7 Birch stand

Upland Mixed Forest

Upland mixed forest is the most widespread of all of the cover types (Table 2.2). The canopy is dominated by a mixture of white spruce with birch and/or aspen. On the margin of black spruce stands, some mixed forests, consisting of black spruce, white spruce, and birch also occur. In these forests, the deciduous species are typically over 100 years old and deciduous species recruitment is limited. The understory is a mixture of species found in forests dominated solely by the respective canopy species.



Figure 2.8 Upland mixed forest stand

Upland White Spruce *Picea glauca*

The upland white spruce stands occurred predominately on south facing slopes but there are some stands on north facing slopes and toe slopes. Many of the white spruce stands in BCEF are relatively old and have survived a number of fires. Other species that commonly occur in upland white spruce forests include: *Alnus crispa* , , *Rosa acicularis*, and *Hylocomium splendens*. Older *Betula neoalaskana* and *Populus tremuloides* trees may also be present, depending on aspect.



Figure 2.9 Upland white spruce stand

Floodplains

The floodplain of BCEF occupies the area adjacent to the Tanana River, a glacially fed, aggrading river (Figure 2.4). Vegetation distribution in the floodplain is driven largely by flood induced primary succession which leads over time to terraces of increasing height in relation to the river (Chapin et al., 2006). A key step in this primary succession is the establishment of *Alnus tenuifolia*, which is a nitrogen fixing keystone species (Ruess et al., 2009; Van Cleve et al., 1993).

Soils in the floodplain are made up of alluvial deposits with varying depths of organic matter depending on the time since last flood deposits. Due to relatively good drainage and thermal mass from the river, soils in the floodplain are generally permafrost free except on some of the oldest terraces (Van Cleve et al., 1996). As with many floodplains throughout interior Alaska the soils along the Tanana River are salt affected and alkaline (Marion et al., 1993). The salt-affected soils initially favor the establishment of salt-tolerant *Salix* sp. (Van Cleve et al., 1993).

Non-acidic Black Spruce *Picea mariana*

Non-acidic black spruce stands occur most commonly on the oldest terraces in the floodplain and in well-drained lowland sites. Other species that commonly occur in the non-acidic black spruce stands are: *Chamaedaphne calyculata*, *Equisetum arvense*, *Larix laricina*, *Rosa acicularis*, and *Saussurea angustifolia*. See (Hollingsworth et al., 2006) for a complete description of non-acidic black spruce communities.



Figure 2.10 Non-acidic black spruce

Balsam Poplar *Populus balsamifera*

Balsam poplar stands occur on terraces 40-100 years old. Other species that commonly occur in balsam poplar forests include: *Alnus tenuifolia* (with lower cover than in the early successional sites), young *Picea glauca*, *Pyrola grandiflora*, *Pyrola secunda* (also common to floodplain white spruce stands), and *Viburnum edule*.



Figure 2.11 Balsam poplar stand

Floodplain White Spruce *Picea glauca*

Floodplain white spruce occurs on older terraces 150-300 years old. The floodplain white spruce cover class is the most extensive cover class in the floodplain (Table 2.2). Other species that commonly occur in floodplain white spruce forests include: *Alnus crispa*, *Betula neolaskana*, *Linnaea borealis*, *Rosa acicularis*, *Pyrola secunda*, *Drepanocladus uncinatus*, *Hylocomium splendens*, *Pleurozium schreberi*, and *Ptilium crista-crastrensis*.



Figure 2.12 Floodplain white spruce stand

Floodplain Early Successional

The floodplain early successional class includes a wide range of early successional sites ranging from initial colonization by salt tolerant *Salix* sp. to the transition to young *Populus balsamifera*. Species that are commonly found at the early successional sites include: *Alnus incana* ssp. *tenifolia* (appears also in balsam poplar stands but has a much higher percent cover in the early successional stands); a number of different forb species: *Antennaria* sp., *Castilleja* sp., *Equisetum hiemale.*, *Equisetum variegatum*, *Erigeron acris*, *Hedysarum Mackenzii*, *Platanthera hyperbore* , *Solidago canadensis*; a number of willow species: *Salix hastata*, *S interior.*, *S. niphoclada*, and *S. pseudomyrsinites* .



Figure 2.13 Floodplain early successional community

Floodplain Mixed Forest

The floodplain mixed forests are typically a combination of older balsam poplar and white spruce; there are a few mixed stands of white spruce and Alaskan birch on older terraces that are less prone to flooding.

Disturbed Sites

Disturbed sites at BCEF vary greatly in species composition and depend on several factors, including type of disturbance, severity of disturbance, and available seed bank (Chapin et al., 2006). The three main disturbance types at BCEF are: fires, flooding, and human use such as timber harvest. Two fires have occurred in recent history in the BCEF region. In 1983, the Rosie Creek Fire burned 1,370 hectares in the uplands and lowlands of BCEF. The Survey Line Fire, in 2001, burned over 6,000 hectares south of the Tanana River. In addition there is continual logging in BCEF also occurs for research purposes and by the general public.

Conclusions

Ultimately the vegetation classes were similar to those used by (Yarie, 1992), who used the life form-based Alaska Vegetation Classification System (Viereck et al., 1992). Because the forest canopy is the dominant spectral feature of the BCEF landscape, it masks whatever floristic relationships may exist in the understory. Also, it is impractical to map more than 15 classes, if you want to ensure high map accuracy. More sample sites would have improved map accuracy and potentially allowed us to conduct more detailed mapping, but sampling was limited to areas with road or river access. Fortunately, an extensive network of primitive roads is present throughout BCEF. Similarly, the meandering nature of the glacially fed Tanana River provides a network of navigable channels to access floodplain areas. The areas with the most difficult access were the lowlands, which consist mainly of wetlands. Accessing the lowlands in the fall after the ground freezes but before the snow falls may be the best option, although collecting floristic data would be challenging.

Despite mapping limitations, preparing a new map of BCEF allows us to capture the changes in plant community composition that have occurred in the 18 year time period since production of the 1992 map and will serve as reference for future vegetation studies.

The map (appendix) has already proven to be useful for an examination of NDVI trends in BCEF by vegetation type (Chapter 3). In addition, the map is currently being

used to determine what plant communities are used by snow shoe hares and their predators (Dashiell Feierabend 2011 personal communication).

References

- Bernhardt, E.L., Hollingsworth, T.N., and Chapin, F. S. III, 2011. "Fire severity mediates climate-driven shifts in understory community composition of black spruce stands in interior Alaska." *Journal of Vegetation Science* no. 22:32-44.
- Chapin, F. S. III, McGuire, A. D., Ruess, R.W., Hollingsworth, T.N., Mack, M.C., Johnstone, J.F., Kasischke, E.S., Euskirchen, E.S., Jones, J.B., Jorgenson, M. T., Kielland, K., Kofinas, G.P., Turetsky, M.R., Yarie, J., Lloyd, A.H., and Taylor, D.L. 2010. "Resilience of Alaska's boreal forest to climatic change." *Canadian Journal of Forest Research* no. 40:1360-1370.
- Clarke, K.R. and Ainsworth, M. 1993. "A method of linking multivariate community structure to environmental variables." *Marine Ecology Progress Series* no. 92:205-219
- Coops, N.C., Johnson, M.E., Alexander, Wulder, M.A., and White, J.C. 2006. "Assessment of QuickBird high spatial resolution imagery to detect red attack damage due to mountain pine beetle infestation." *Remote Sensing of Environment* no. 103:67-80.
- Euskirchen, E.S., McGuire, A. D., Chapin, F. S. III, Yi, S., and Thompson, C.C. 2009. "Changes in vegetation in northern Alaska under scenarios of climate change, 2003-2100: implications for climate feedbacks." *Ecological Applications* no. 19 (4):1022-1043.

- Hollingsworth, T.N., M.D. Walker, Chapin, F. S. III., and Parsons, A.L. 2006. "Scale-dependent environmental controls over species composition in Alaskan black spruce communities." *Canadian Journal of Forest Research* no. 36 (7):1781-1796.
- Hulten, E. 1968. *Flora of Alaska and Neighboring Territories*. Stanford: Stanford University Press.
- Johnstone, J.F., Chapin, F. S. III, Hollingsworth, T.N., Mack, M.C., Romanovsky, V.E., and Turetsky, M.R. 2010. "Fire, climate change, and forest resilience in interior Alaska." *Canadian Journal of Forest Research* no. 40:1302-1312.
- Johnstone, J.F. and Kasischke, E. 2005. "Stand-level effects of soil burn severity on postfire regeneration in a recently burned black spruce forest." *Canadian Journal of Forest Research* no. 35:2151-2163.
- Kielland, K., Bryant, J.P., and Ruess, R.W. 1997. "Moose herbivory and carbon turnover of early successional stands in interior Alaska." *Oikos* no. 80 (1):25-30.
- Marion, G.M., Van Cleve, K., Dyrness, C.T., and Black, C.H. 1993. "The soil chemical environment along a forest primary successional sequence on the Tanana River floodplain, interior Alaska." *Canadian Journal of Forest Research* no. 23:914-922.
- McCune, B. and Grace, J.B. 2002. *Analysis of Ecological Communities*. Glenden Beach, Oregon, U.S.A.: MjM Software Design.

- McCune, B. and Medford, M.J. 1999. PC-ORD. *Multivariate Analysis of Ecological Data 5.0*. Glenden Beach, Oregon, U.S.A.: MjM Software Design.
- McGuire, A. D., Wirth, C., Apps, M., Bhatti, J., de Groot, B., Beringer, J., Clein, J., Chapin, F. S. III, Walker, D., Epstein, H., Jia, G. J., Kicklighter, D. W., Melillo, J., Efremov, D., Eugster, W., Fukuda, M., Gower, T., Hinzman, L., Huntley, B., and Kasischke, E. 2002. "Environmental variation, vegetation distribution, carbon dynamics and water/energy exchange at high latitudes." *Journal of Vegetation Science* no. 13 (3):301.
- Mueller-Dombois, D. and Ellenberg, H. 1974. *Aims and Methods of Vegetation Ecology*. New York: John Wiley & Sons.
- Ruess, R.W., McFarland, J.M., Trummer, L.M., and Rohrs-Richey, J.K. 2009. "Disease-mediated declines in N-fixation inputs in *Alnus tenuifolia* to early-successional floodplains in interior and south-central Alaska." *Ecosystems* no. 12:489-502.
- Schickhoff, U., Greifswald, Walker, M.D., and Walker, D.A. 2002. "Riparian willow communities on the Arctic Slope of Alaska and their environmental relationships: A classification and ordination analysis." *Pythocoenologia* no. 32 (2):145-204.
- Smart, D. 2008. *Remote sensing aspen leaf miner (Phyllocnistis populiella Chamb) infestations near Ester Dome in Fairbanks, Alaska*, Department of Forest Sciences, University of Alaska Fairbanks, Fairbanks, Alaska.

- Stohlgren, T.J., Chong, G.W., Kalkhan, M.A., and Schell, L.D. 1997. "Multiscale sampling of plant diversity: Effects of minimum mapping unit size." *Ecological Applications* no. 7 (3):1064-1074.
- Van Cleve, K., and Dyrness, C.T. 1983. "Conclusions and directions for future research in taiga forest ecosystems." *Canadian Journal of Forest Research* no. 13:914-916.
- Van Cleve, K., Viereck, L. A., and Dyrness, C.T. 1996. "State factor control of soils and forest succession along the Tanana River in interior Alaska." *Arctic and Alpine Research* no. 28 (3):388-400.
- Van Cleve, K., Yarie, J., Viereck, L. A., and Dyrness, C.T. 1993. "Conclusions on the role of salt-affected soils in primary succession on the Tanana River floodplain, interior Alaska." *Canadian Journal of Forest Research* no. 23:1015-1018.
- Viereck, L. A., Dyrness, C.T., Batten, A.R., and Wenzlick, K.J. 1992. Alaska vegetation classification. In *General Technical Report: USDA Forest Service*.
- Vitt, D.H., Marsh, J.E., and Bovey, R.B. 1988. *Mosses Lichens and Ferns of Northwest North America*. Vancouver, B.C.: Lone Pine Publishing.
- Volney, W. Jan A., and Fleming, Richard A. 2000. "Climate change and impacts of boreal forest insects." *Agriculture, Ecosystems & Environment* no. 82 (1-3):283.
- Walker, M.D., Walker, D.A., and Auerbach, N.A. 1994. "Plant communities of a tussock tundra landscape in the Brooks Range Foothills, Alaska." *Journal of Vegetation Science* no. 5:843-866.

- Werner, R. 2010. Bonanza Creek Experimental Forest defoliating insect population levels per leaf beginning 1975. edited by Bonanza Creek LTER. Fairbanks, AK.
- Westhoff, V. and van der Maarel, E. 1978. "The Braun-Blanquet approach." In *Classification of Plant Communities*, edited by Whittaker and R.H., 289-399.
- Yarie, J. 1992. Vegetation for the Bonanza Creek Long-Term Ecological Research Area. Fairbanks: University of Alaska Fairbanks.

Chapter 3 Assessment of Change in Vegetation Index in Bonanza Creek

Experimental Forest

Abstract

The objective of this study was to examine trends in vegetation index (NDVI) in the study area using high resolution satellite imagery and a hierarchical approach by assessing trends: 1) throughout the study area and in different landscape positions, 2) by topographic class, 3) after wildfire, and finally 4) in different plant communities. To do this I compiled 11 Landsat TM and ETM+ images from the years 1986-2009. The images were co-registered and radiometrically rectified and NDVI was calculated. I found a negative trend in the entire study area that is consistent with other studies examining NDVI trends in the area. The negative trend was also similar throughout different landscape and topographic positions. There were some differences in trends in plant communities with floodplain communities exhibiting a stronger negative trend than upland communities. As expected, the two recently burned areas exhibited positive NDVI trends following the fires.

Introduction

General circulation climate models predict warming will occur most rapidly at high latitudes (Chapin et al., 2006; Hansen et al., 2006; Ramaswamy et al., 2001). As evidence for this high latitude amplification, global temperature has increased approximately 0.8° C in the past 100 years, while in Alaska the rise in average temperature has been approximately 1.4° C and in interior Alaska, 2.2° C in the last fifty

years (Stafford et al., 2000; Wendler et al., 2009). Along with this rise in temperature the growing season length in the interior Alaska has increased by 45% in the last 100 years, with no significant increase in precipitation (Wendler et al., 2009).

The boreal forest is the dominant forested ecosystem in northern latitudes and the largest forested biome in the world, covering 18.5 million square km and comprising approximately 25% of the forested land (Chapin et al., 2006). There was a shift in summer climate regime in boreal Alaska during the mid-1970s, and 2004 was the warmest summer in the past 200 years (Barber et al., 2004). In a region where growing season precipitation can be less than 200 mm, a warming climate can lead to temperature-induced drought stress (Barber et al., 2000; D'Arrigo et al. 2004). The effects of climate warming in the boreal forest can lead to other changes including increased insect disturbance (Volney et al., 2000), thawing permafrost (Jorgenson et al., 2010), changes in nutrient cycling (Schimel et al., 2006), changes in carbon allocation (Eissenstat et al., 2000), drought-induced, regional-scale mortality (Michaelian et al., 2011), and increased fire frequency and severity (Kasischke et al., 2010). All of these factors have a direct effect on vegetation, both in terms of biomass and productivity (Chapin et al., 2010).

The remotely sensed normalized difference vegetation index (NDVI) is a useful tool for monitoring changes in plant biomass and productivity on a landscape-scale (Pettorelli et al., 2005). Early hypotheses predicted that NDVI would increase in northern latitudes with rising temperatures due to increased length of growing season and nutrient cycling (Cao et al., 1998; Myneni et al., 1997). The arctic tundra has exhibited

increases in NDVI in association with a warming climate (Goetz et al., 2005; Jia et al., 2003; Verbyla., 2008). However, several studies have shown the opposite effect in the mid-latitudes and in the arctic (Angert et al., 2005) including interior Alaska boreal forests (Beck et al., 2011; Goetz et al., 2005; Parent et al., 2010; Verbyla, 2008).

It is clear that there has been a regional “browning trend” over the past two decades in eastern boreal Alaska, based on several NDVI studies at different spatial and temporal scales (Beck et al., 2011; Goetz et al., 2005; Parent et al., 2010; Verbyla, 2008). The goal of this study is to begin to understand what patches on the landscape are contributing strongly to the observed regional NDVI trend. Vegetation in this region is distributed in a complex mosaic resulting from disturbance legacies and microclimate. We expected warmer sites, such as south-facing slopes, to have a stronger decline in NDVI trends relative to cooler sites such as permafrost-dominated north-facing slopes or wetter sites such as floodplain or wetland patches. The objectives of this study were to investigate NDVI trends within polygons or aggregated pixels using a time series of 30 meter pixels from Landsat sensors. In this paper I investigate NDVI trends at a variety of scales including: 1) throughout the study area and in different landscape positions, 2) by topographic class, 3) after wildfire, and finally 4) in different plant communities.

Methods

Study Area

My study was conducted in the Bonanza Creek Experimental Forest (BCEF), which is one of two research sites for the Bonanza Creek Long Term Ecological Research

(LTER) program. BCEF is located in interior Alaska approximately 20 km south of Fairbanks and encompasses over 5,000 hectares. The area is a representative cross-section of boreal landscapes including uplands, lowlands, and the floodplain of the glacially fed Tanana River at low elevation and a variety of boreal forest types in the upland landscape.

Interior Alaska is bounded to the south by the Alaska Range and to the north by the Brooks Range. The region has a continental climate with a mean annual temperature of -2.2° Celsius and a mean annual precipitation of approximately 280 mm (Hammond et al., 1996; Wendler et al., 2009). Average growing season length is 123 days, an increase of 45% over the past century (Wendler et al., 2009).

Fire is the dominant landscape disturbance in interior Alaska ecosystems and there have been two fires at BCEF in the past 30 years (Figure 3.1). In 1983 the Rosie Creek fire burned 3,400 hectares, over 1,300 of which were in BCEF, burning both lowland and upland landscapes. The Survey Line fire, in 2001, burned over 6,000 hectares in the Tanana River floodplain and lowlands. Both fires were human caused and started in June.

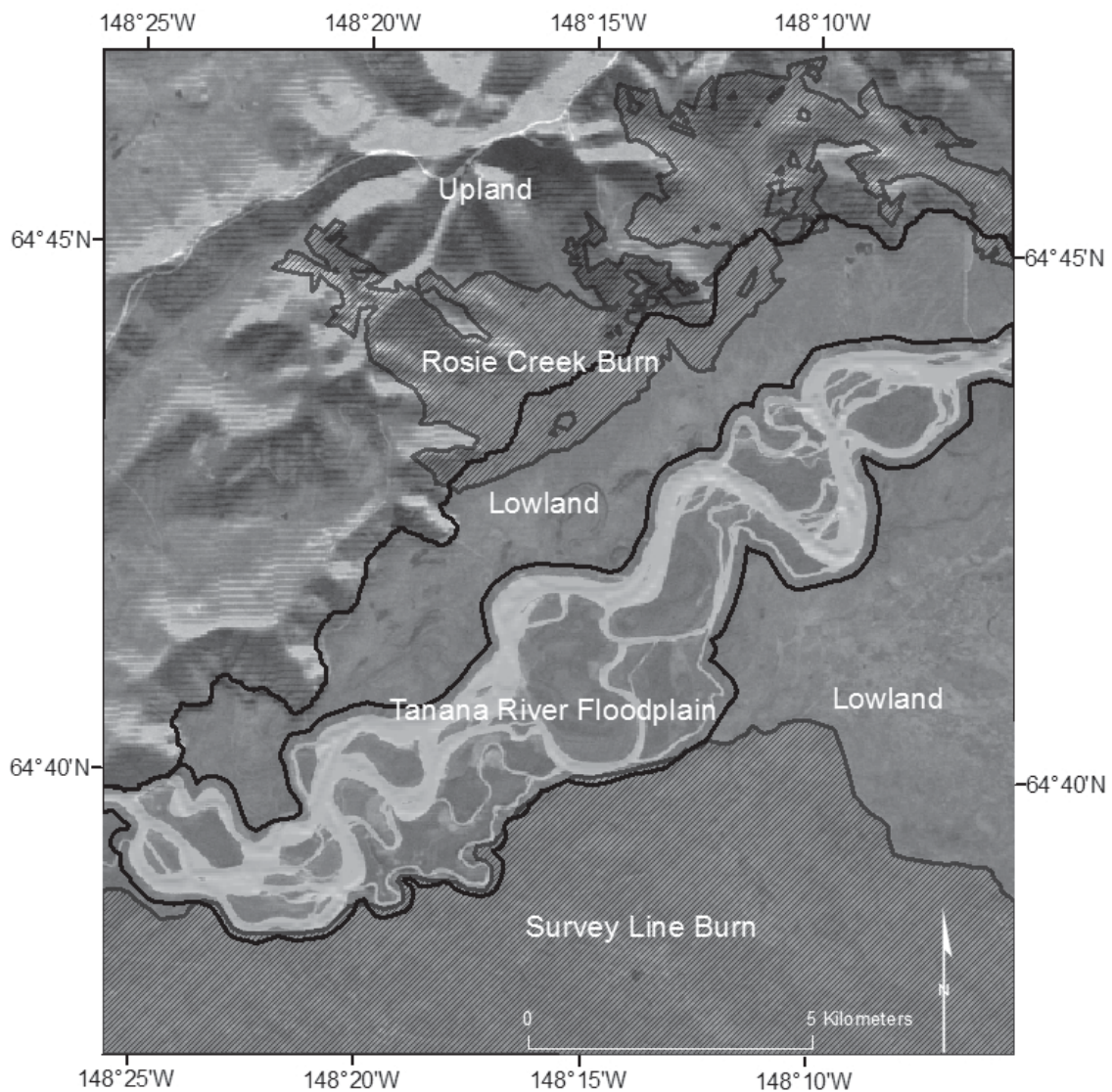


Figure 3.1 Landscape units used for analysis

Soil development in the study area, which was unglaciated during the last glacial maximum, varies depending on landscape position. Most of the soils in the uplands are the result of deep loess deposition from the Tanana River (Chapin et al., 2006). The lowland soils have a thick organic horizon over loess. In the Tanana River floodplain the

soils are the result of alluvial deposition resulting in salt-affected soils due to the glacial sediments and evaporation of shallow ground water (Van Cleve et al., 1996). Soil moisture on the Tanana River floodplain can be influenced by river level as there is a close relationship between river stage, ground water level, and soil moisture (Viereck et al., 1993). Since the main source of the Tanana River is glaciers from the Alaska Range, there is a positive correlation of July-August discharge with temperature, and a negative correlation with precipitation (Nossov et al., 2010).

Interior Alaska is within the zone of discontinuous permafrost and its presence is controlled by topographically driven microclimate. In the study area permafrost is intermittent in the uplands with north-facing slopes and valley bottoms typically having permafrost. Permafrost distribution in the lowlands and floodplain landscapes is controlled by subsurface water flow and the presence or absence of an insulating moss layer (Chapin et al., 2006).

Processing Landsat sensor data

Regional studies investigating NDVI from a variety of sensors at different spatial and temporal scales have found a declining trend in NDVI over the past two decades in interior Alaska boreal forests (Beck et al., 2011, Parent and Verbyla 2010). In order to investigate what areas of the boreal landscape are strongly influencing this regional trend at a finer (30-meter pixel) spatial scale, I used NDVI computed from a time series of Landsat sensors (Table 3.1). The Landsat images were downloaded from the United States Geological Survey (USGS) website (<http://glovis.usgs.gov/>) and the Global Land

Cover Facility (GLCF) website (<http://www.landcover.org>). Landsat TM and ETM+ images were chosen based on two primary criteria: 1) they were all from 20 June to 16 August (Table 3.1) so they should be phenologically similar in terms of seasonal peak NDVI (Figure 3.2) and 2) they were all relatively cloud free, and they were from one of two scenes that cover the study area. All other available Landsat scenes of the study area were omitted due to phenological stage or high-cloud cover.

Table 3.1 Landsat scenes used for analysis. Images with cloud cover were masked to eliminate cloud effects on NDVI analysis.

Year	Date	Satellite and Sensor	Path/Row	Cloud Masking
1986	July 1	Landsat 5-TM	70/15	No
1991	June 22	Landsat 5-TM	69/15	No
1995	August 11	Landsat 5-TM	70/15	No
1999	June 19	Landsat 5-TM	70/15	Yes
2000	August 16	Landsat 7-ETM+	70/15	No
2001	June 16	Landsat 7-ETM+	70/15	No
2002	August 6	Landsat 7-ETM+	70/15	No
2003	August 10	Landsat 5-TM	69/15	No
2006	August 9	Landsat 5-TM	70/15	No
2008	June 20	Landsat 5-TM	69/15	Yes
2009	June 30	Landsat 5-TM	70/15	Yes

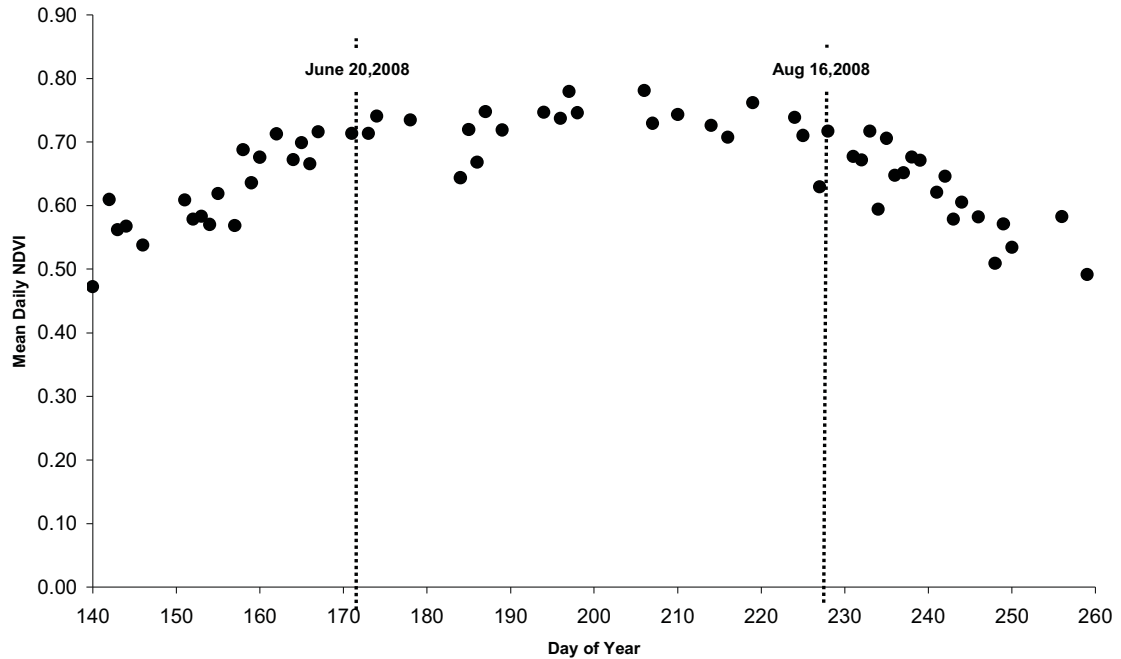


Figure 3.2 Mean daily MODIS NDVI values for 2008 within Path70 Row15 Landsat scene area, illustrating peak seasonal green up. Daily NDVI variations in this time series are likely due to variation in vegetation type (broadleaf and coniferous composition) in each cloud-screened daily mean NDVI.

Landsat sensor images were co-registered to a Landsat sensor GeoCover orthorectified image from August 16, 2000 from the Global Landcover Facility (NASA, EarthSat Orthorectification) in the UTM/WGS84 coordinate system. In co-registering each image a minimum of 30 ground control points was used and each linear co-registration model had an RMS positional error of less than 15 meters (0.5 pixels). Nearest neighbor sampling was used during the co-registration to retain the original pixel spectral values.

After co-registration pixel values were converted to a common radiometric scale of spectral reflectance using methods described in Chander et al. (2009). Red and near-infrared (NIR) spectral reflectance values were then normalized for variable atmospheric conditions using a radiometric regression method (Hall et al., 1991). Eighty pseudo invariant features, 40 bright and 40 dark, were used to develop regression models to normalize spectral reflectance values to the base image, from August 11, 1995. In each case the coefficient of determination was >0.95 and both red and NIR spectral reflectance were radiometrically adjusted using this method. Non-vegetated pixels and clouds were then excluded using two techniques: 1) by excluding all pixels with an NDVI value less than or equal to 0.3, and 2) by masking out cold cloud pixels using the thermal band of the Landsat images.

Dividing the Bonanza Creek Experimental Forest landscape

The landscape was divided in a spatial hierarchy to allow for an examination of NDVI trends first in the entire BCEF area, then at smaller spatial scales of landscape units (uplands, lowlands, and active floodplain) (Figure 3.1), topographic units (valley bottoms, north-facing, and south-facing slopes), and finally by vegetation type. Due to the large area affected by fire I also investigated the NDVI response of a 1983 and a 2001 burn within BCEF.

To separate BCEF into the three landscape units used in the analysis I used a combination of methods. The uplands were defined using a National Elevation Dataset (NED) 2 arc second digital elevation model (DEM) acquired from the National Elevation

Dataset website (<http://ned.usgs.gov>) that was projected to UTM 30-meter pixels. Ten meter contour lines were generated from the model and the uplands were defined using the contour line at the base of the steepest slope. The active floodplain was defined using a combination of a 200 meter buffer around the Tanana River and the lowest elevation contours from the NED 2 arc second DEM. Finally, the lowland was defined as the remaining area (Figure 3.1).

The uplands were further divided based on aspect and slope. The north and south facing uplands were defined by creating an aspect layer using the UTM elevation grid. Slopes with an aspect between 315° and 45° were defined as north facing and slopes with an aspect between 135° and 225° were defined as south facing. Finally, the valley bottoms in the uplands were defined using a method developed by the U.S.D.A. Forest Service Boise Aquatic Science lab (Nagel, 2007).

Burn polygons were mapped from post-fire satellite images. An outline of the Rosie Creek burn was created from a June 24, 1983 Landsat 4 MSS, Path 69 Row 15 image. This Landsat scene was chosen since it was acquired days after the fire was extinguished, which resulted in the fire scar on the image having a high resolution. A threshold of NIR band values was used to map burned from unburned areas and the resulting polygons were modified based on higher resolution imagery of the area (Figure 3.1). The Survey Line fire, which occurred in June 2001, impacted approximately 6000 hectares in the lowlands south of the Tanana River. The outline of the Survey Line burn was derived from the U.S. Bureau of Land Management's Wildland Fire Dataset for

Alaska (U.S. Dept. of Interior, 2010) and interpretation of the imagery acquired shortly after the fire (Figure 3.1).

For analysis of NDVI trends in different vegetation types I used a polygon based vegetation map of the area. The map was produced in May of 2010 based on a floristic classification of vegetation in BCEF. The floristic classification was developed using data from 85 field sites and led to twelve vegetation classes (Table 3.2). The twelve vegetation classes were divided largely based on landscape position. In the uplands there were six vegetation classes: birch forest, aspen forest, white spruce forest, mixed deciduous and white spruce forest, disturbed fire, and acidic black spruce forests. In the floodplain there were seven vegetation classes: deciduous forest, white spruce forest, mixed deciduous and white spruce forest, disturbed fire, disturbed clear-cut, early successional and non-acidic black spruce. Black spruce classification followed Hollingsworth et al. (2006) where acidic and non-acidic black spruce communities differ mainly in drainage, with well-drained sites typically being non-acidic. Polygons were drawn based on the classification and inspection of high-resolution, 1.5 m² pixels, satellite imagery of the area (Chapter 2).

Table 3.2 Vegetation classes used for analysis of NDVI trends

Vegetation Class	Sample Size (number of pixels)	Area (hectares)	Number of polygons
<i>Black Spruce</i>	7,602		62
<i>Acidic Black Spruce</i>	3,307	1,357	11
<i>Non-Acidic Black Spruce</i>	3,150	1,202	41
<i>Deciduous</i>	2,647		97
<i>Aspen</i>	680	345	7
<i>Balsam Poplar</i>	722	280	62
<i>Birch Forest</i>	940	438	8
<i>Mixed Forest</i>	7,581		71
<i>Upland Mixed Forest</i>	6,670	2,783	21
<i>Floodplain Mixed Forest</i>	678	293	41
<i>White Spruce</i>	4,976		73
<i>Upland White Spruce</i>	1,689	688	11
<i>Floodplain White Spruce</i>	3,124	1,261	62
<i>Early Successional</i>			
<i>Floodplain Early Successional</i>	1,387	678	106
<i>Wetland</i>	1,572		71
<i>Scrub Wetland</i>	207	82	16
<i>Open Wetland</i>	1,360	540	55

Results

NDVI trends by study area and landscape position

Across the study site there was a significant decrease in NDVI values, over the years I examined, regardless of the inclusion of burns (Table 3.3). Each of the landscape units: uplands, lowlands, and floodplain, exhibited a similar negative trend (Figure 3.3 and Table 3.3). The strongest positive correlation in terms of interannual mean NDVI

within the three landscape units was between the uplands and the floodplain (Table 3.4). NDVI was higher in the uplands than both the lowlands and floodplain throughout the years examined (Figure 3.3); most likely due to the higher proportion of deciduous stands in the uplands than the other two landscape divisions. There was a consistent large increase in NDVI across all landscape units in 2000 (Figure 3.3), however this increase did not significantly affect the overall negative trend exhibited.

Table 3.3 1986-2009 mean NDVI linear regression trends by subsample area (n= 11 years)

	Including Burns:				Excluding Burns:			
	Sample Size (number of pixels)	r ²	slope	p-value	Sample Size (number of pixels)	r ²	slope	p-value
BCEF	193,559	0.70	-0.0028	0.001	135,263	0.75	-0.0029	0.001
<u>Uplands</u>	81,893	0.39	-0.0014	0.042	64,378	0.65	-0.0027	0.003
<i>North facing</i>	24,648	0.67	-0.0024	0.002	22,424	0.74	-0.0030	0.001
<i>South facing</i>	37,206	0.20	-0.0011	0.162	26,735	0.55	-0.0027	0.009
<i>Rosie Creek Burn</i>	21,552	0.60	0.0026	0.005				
<i>Valley Bottoms</i>	27,192	0.32	-0.0013	0.072	18,799	0.72	-0.0031	0.001
<u>Lowlands</u>	90,291	0.66	-0.0044	0.002	64,331	0.75	-0.0034	0.001
<i>Survey Line Burn</i>	45,005	0.53	-0.0059	0.011				
<u>Floodplains</u>	25,201	0.63	-0.0029	0.004	24,328	0.62	-0.0028	0.004

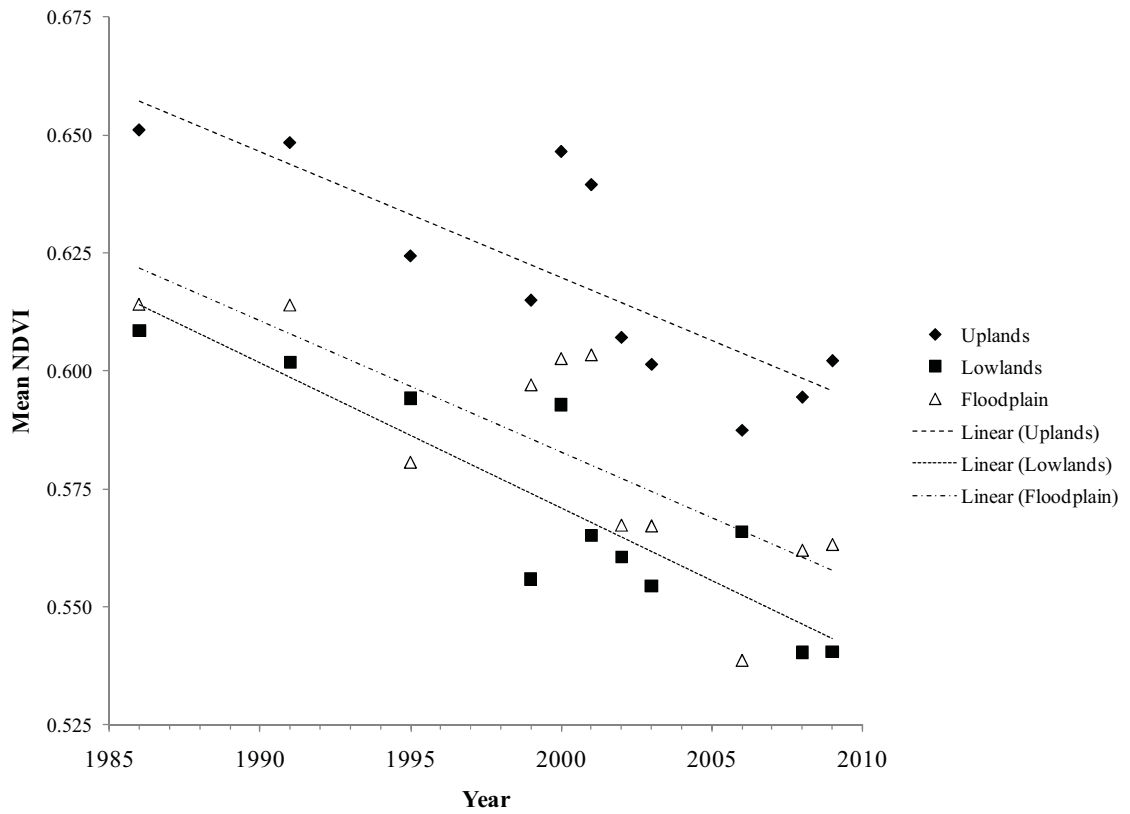


Figure 3.3 1986-2009 trend in mean NDVI value by landscape position within the study area (excluding burned pixels) (n=11 years).

Table 3.4 Correlation matrix of annual residuals for 1986-2009 trend in mean NDVI value by landscape position within the study area (excluding burned pixels) (n=11 years).

	Uplands	Lowlands	Floodplain
Uplands	1.00		
Lowlands	0.35	1.00	
Floodplain	0.86	-0.12	1.00

NDVI trends by topographic class

When burns were excluded, all of the remaining uplands examined, north and south-facing slopes and upland valley bottoms, exhibited a significant negative trend in NDVI over time (Table 3.3). In general the NDVI values were higher on south facing slopes than on north facing slopes but the trend was similar (Figure 3.4); the higher NDVI values on south facing slopes compared to north facing slopes is most likely due to a higher proportion of broadleaf deciduous stands. As with the entire study site, an increase in NDVI in 2000 was observed on both north and south-facing slopes (Figure 3.4). There was not a strong correlation in terms of interannual mean NDVI within the three topographic classes (Table 3.5)

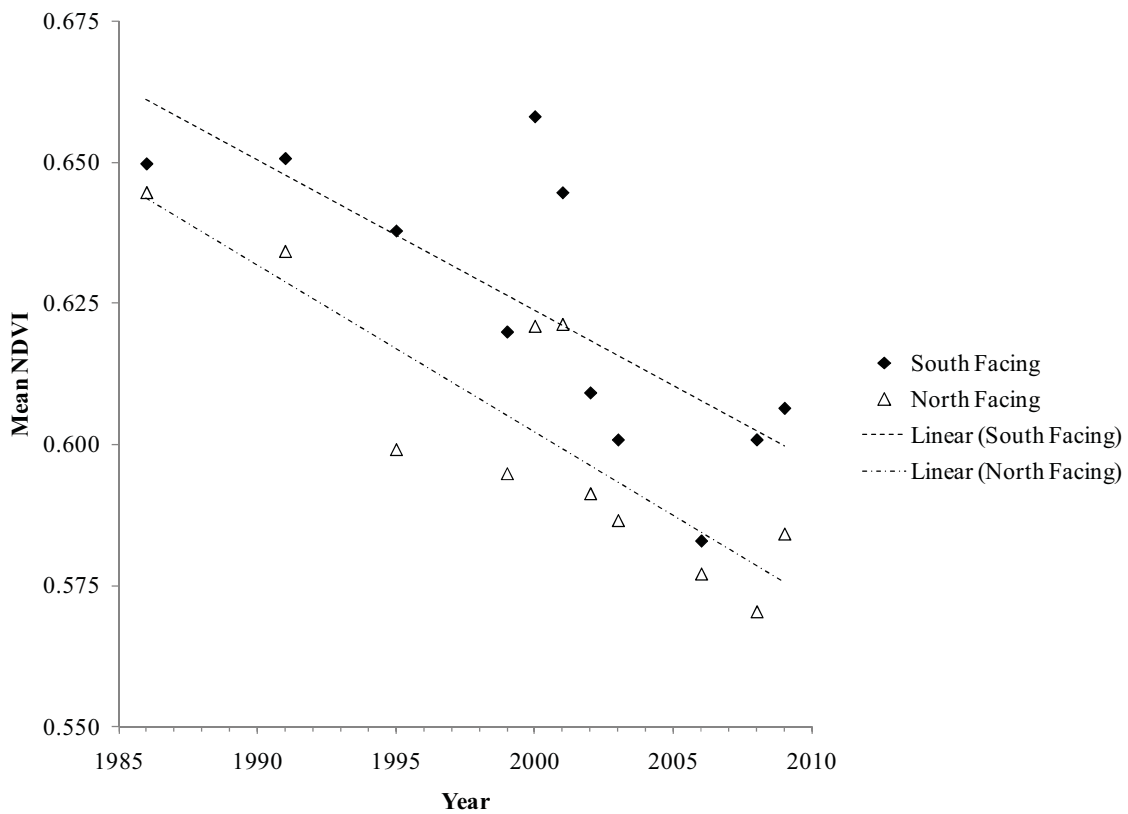


Figure 3.4 1986-2009 trend in mean NDVI value for unburned upland south and north facing slopes within the study area (n=11 years).

Table 3.5 Correlation matrix of annual residuals for 1986-2009 trend in mean NDVI value by slope class within the study area (excluding burned pixels) (n=11 years).

	North Facing	South Facing	Valley Bottoms
North Facing	1.00		
South Facing	0.39	1.00	
Valley Bottoms	-0.10	0.58	1.00

Influence of wildfire

The two burns that occurred in the summers of 1983 (Rosie Creek fire) and 2001 (Survey Line fire) impacted a large proportion of BCEF (Figure 3.1). The area burned in the Rosie Creek fire showed a significant positive trend in NDVI post-fire (Figure 3.5 and Table 3.3). The mean NDVI within this burn had a similar interannual pattern relative to unburned uplands after 2000 (Figure 3.6). Vegetation in the Survey Line burn displayed a negative trend in NDVI prior to the fire, and a contrasting positive trend following the fire (Figure 3.5). The area burned in the Survey Line fire and unburned lowlands both exhibited a significant negative trend in NDVI until the fire of 2001 (Figure 3.7). Following the fire, the mean NDVI values in the burned area increased and nearly equal the unburned lowlands by 2009 (Figure 3.7).

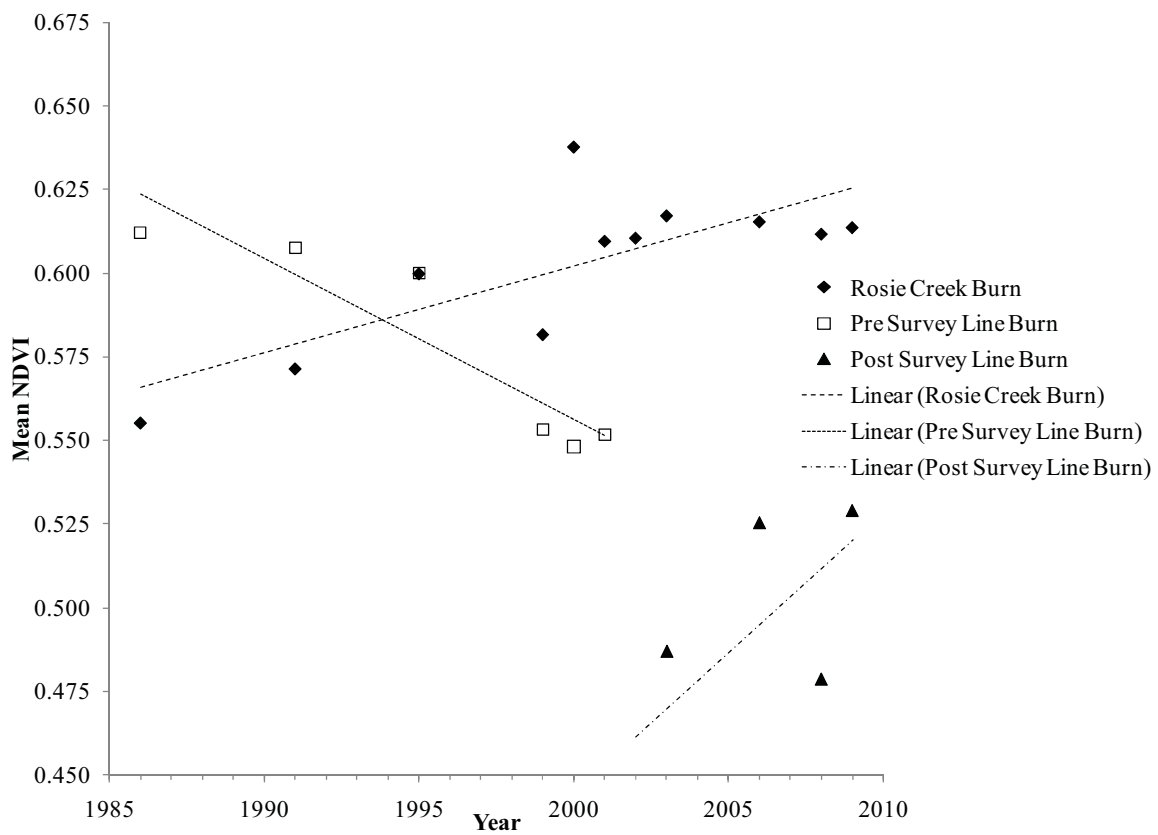


Figure 3.5 1986-2009 trend in mean NDVI value the 1983 Rosie Creek burn area and the 2001 Survey Line burn area (n=11 years).

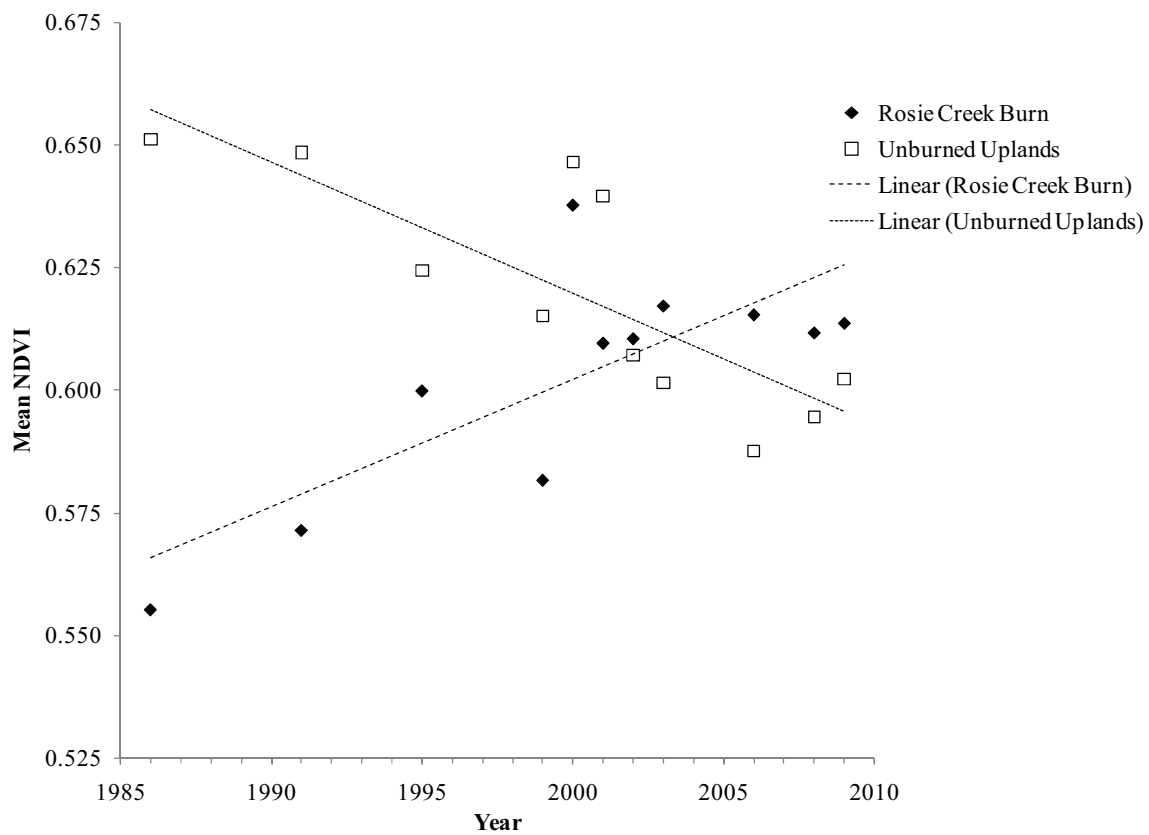


Figure 3.6 1986-2009 trend in mean NDVI value from the 1983 Rosie Creek burn and the unburned uplands (n=11 years).

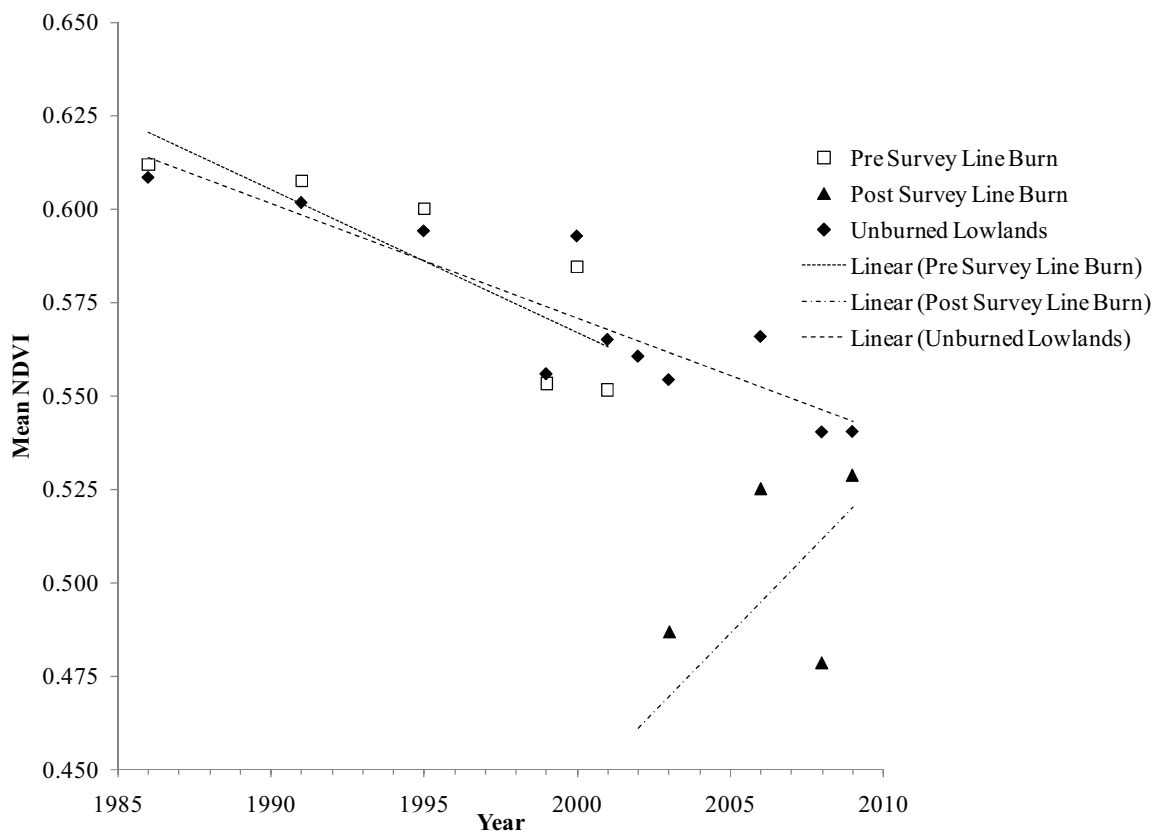


Figure 3.7 1986-2009 trend in Mean NDVI value from the 2001 Survey Line burn area and the unburned lowlands (n=11 years).

Influence of vegetation type

Across the study area, the four major forest types (black spruce, deciduous, mixed, and white spruce), had similar negative trends in NDVI (Table 3.6). However, some vegetation types showed stronger trends depending on location (i.e. landscape unit). White spruce and mixed forests showed a stronger negative response in the floodplain versus uplands (Table 3.6 and Figure 3.8). Aspen stands did not exhibit a significant trend (Table 3.6) and this is due to two outlier years with relatively low NDVI values 1986 and 2006, which when excluded from the analysis allow for a significant trend

(Figure 3.9). The low NDVI values in 1986 and 2006 are likely due to the high occurrence of defoliator insects those years (Werner, 2010). Both upland broadleaf deciduous (birch) and conifer (white spruce) exhibited a similar negative NDVI trend (Table 3.6 and Figure 3.10). A correlation matrix of NDVI trends for upland and floodplain white spruce and birch stands shows a strong correlation between upland and floodplain white spruce and between floodplain white spruce and between floodplain white spruce and birch stands (Table 3.7).

Table 3.6 1986-2009 mean NDVI linear regression trends by vegetation class subsample area (n= 11 years)

Vegetation Type	Sample Size (number of pixels)	r ²	slope	df	F-value	p-value
<i>Black Spruce</i>	32,068	0.78	-0.0030	1,10	31.06	0.000
<i>Acidic Black Spruce</i>	14,450	0.75	-0.0030	1,10	27.56	0.001
<i>Non-Acidic Black Spruce</i>	13,214	0.72	-0.0028	1,10	26.20	0.001
<i>Deciduous</i>	13,002	0.42	-0.0030	1,10	6.39	0.032
<i>Aspen</i>	3,806	0.09	-0.0024	1,10	0.86	0.377
<i>Balsam Poplar</i>	3,054	0.79	-0.0037	1,10	37.82	0.000
<i>Birch Forest</i>	4,854	0.52	-0.0029	1,10	9.61	0.013
<i>Mixed Forest</i>	35,047	0.64	-0.0031	1,10	15.70	0.003
<i>Upland Mixed Forest</i>	31,514	0.61	-0.0030	1,10	14.33	0.004
<i>Floodplain Mixed Forest</i>	3,121	0.73	-0.0045	1,10	24.60	0.001
<i>White Spruce</i>	21,073	0.46	-0.0029	1,10	7.62	0.022
<i>Upland White Spruce</i>	7,632	0.28	-0.0019	1,10	3.51	0.094
<i>Floodplain White Spruce</i>	13,441	0.53	-0.0036	1,10	10.07	0.011
<i>Floodplain Early</i>						
<i>Early Successional</i>	6,958	0.52	-0.0016	1,10	9.92	0.004
<i>Successional</i>						
<i>Wetland</i>	6,837	0.23	-0.0020	1,10	2.74	0.132
<i>Scrub Wetland</i>	913	0.36	-0.0021	1,10	5.04	0.051
<i>Open Wetland</i>	5,924	0.22	-0.0019	1,10	2.50	0.148

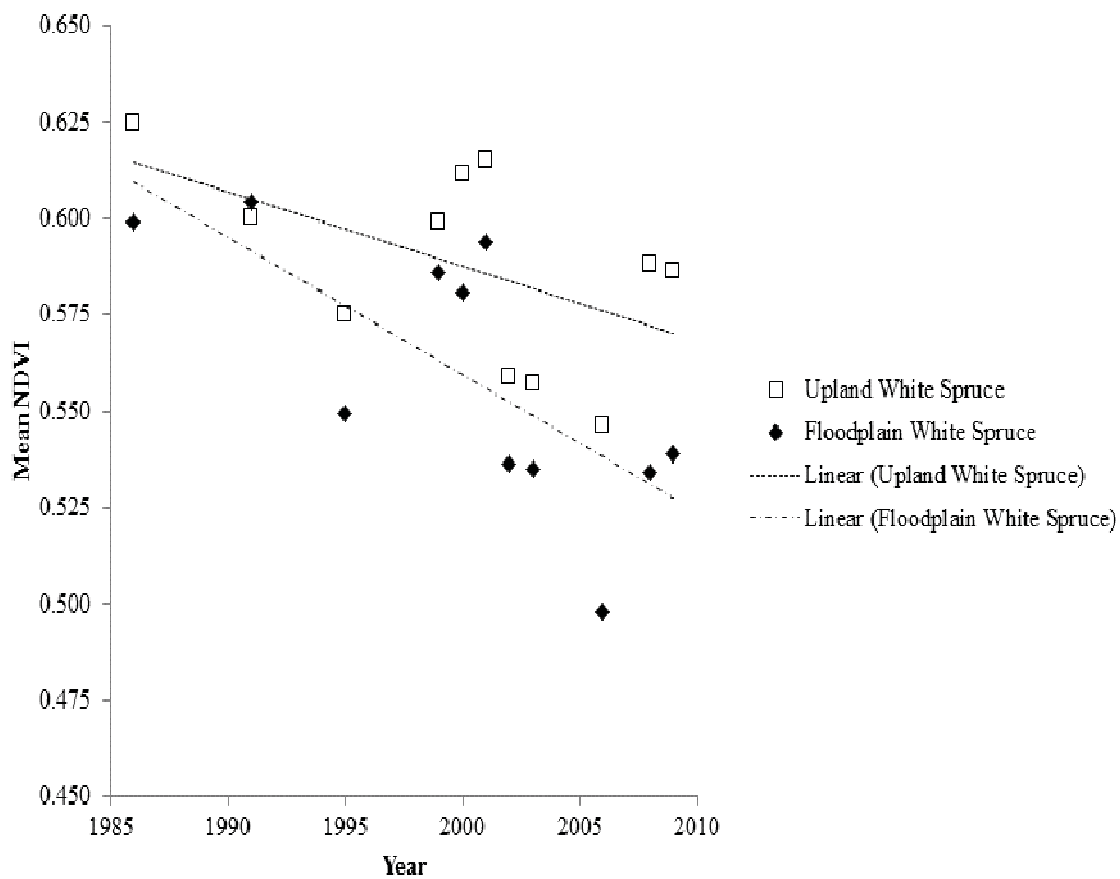


Figure 3.8 1986-2009 trend in Mean NDVI value for upland and floodplain white spruce (n=11 years).

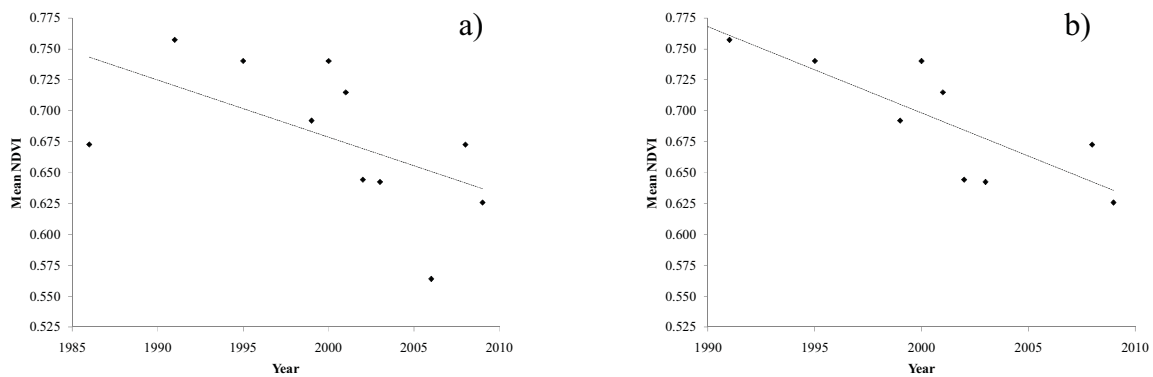


Figure 3.9 1986-2009 trend in Mean NDVI value for aspen forests: (a) all dates included (n=11 years) and (b) high defoliator insect year scenes excluded (aspen leaf tortrix in 1986 and aspen leaf miner in 2006) (n=9 years).

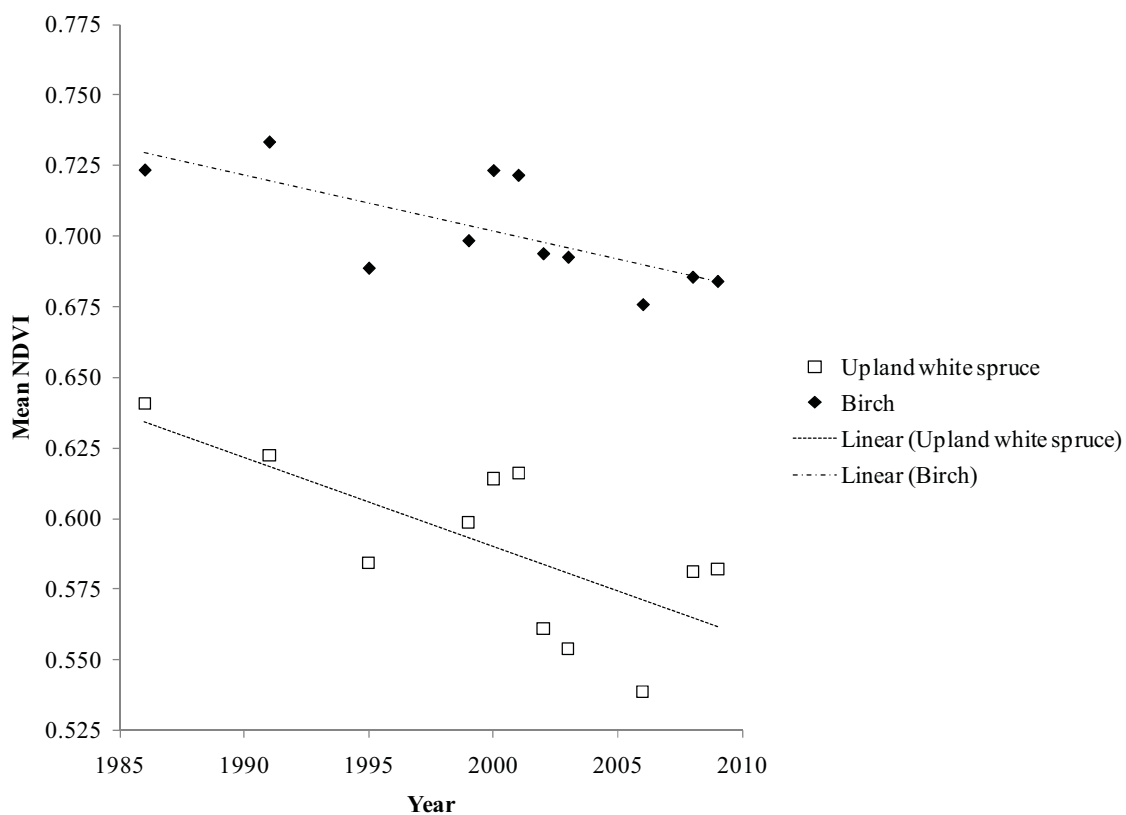


Figure 3.10 1986-2009 trend in Mean NDVI value for upland deciduous (birch) conifer (white spruce) (n=11 years).

Table 3.7 Correlation matrix of annual residuals for 1986-2009 trend in mean NDVI value by vegetation class within the study area (excluding burned pixels) (n=11 years).

	Upland White Spruce	Floodplain White Spruce	Birch
Upland White Spruce	1.00		
Floodplain White Spruce	0.91	1.00	
Birch	0.73	0.87	1.00

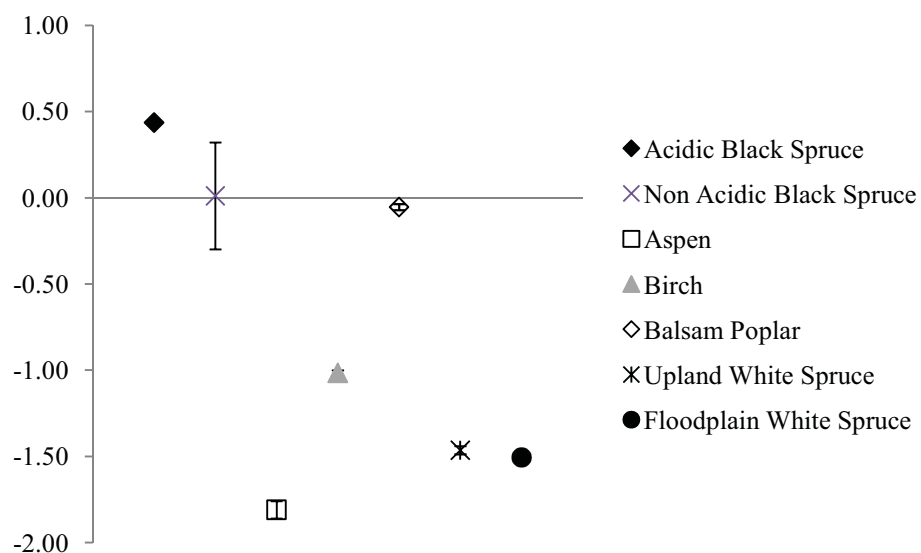


Figure 3.11 Residuals for selected vegetation types from 2006 following the 2004 drought

In 2004, interior Alaska experienced record warm and dry conditions leading to severe drought (Richmond et al., 2005). An examination of the NDVI response from 2003 to 2006 illustrates varied responses by different vegetation types (Figure 3.11). Aspen had the strongest negative divergence from the trend while the two black spruce forest types and balsam poplar did not diverge significantly from the trend (Figure 3.11).

There were a total of 466 individual polygons that fell into the vegetation classes I analyzed. Of the 466 polygons 14 had a significant positive trend and 248 had a significant negative trend. The only vegetation classes with positive trends were birch, balsam poplar, and floodplain early successional (Table 3.8). The scrub wetland vegetation class had the smallest percentage of negative trending polygons (Table 3.8). The acidic black spruce class had the highest percentage of negative trending polygons.

Table 3.8 1986-2009 trend in mean NDVI value by for individual polygons by vegetation class within the study area (p-value < 0.01) (excluding burned pixels) (n=11 years).

Vegetation Type		Number of Polygons		
		Total	increasing NDVI	decreasing NDVI
<i>Black Spruce</i>	<i>Acidic Black Spruce</i>	11	0	9 (82%)
	<i>Non-Acidic Black Spruce</i>	41	0	32 (78%)
<i>Deciduous</i>	<i>Aspen</i>	7	0	3 (43%)
	<i>Balsam Poplar</i>	62	1	44 (71%)
	<i>Birch Forest</i>	8	1	5 (62%)
<i>Mixed Forest</i>	<i>Upland Mixed Forest</i>	21	0	16 (76%)
	<i>Floodplain Mixed Forest</i>	41	0	31 (76%)
<i>White Spruce</i>	<i>Upland White Spruce</i>	11	0	6 (54%)
	<i>Floodplain White Spruce</i>	62	0	45 (75%)
<i>Early Successional</i>	<i>Floodplain Early Successional</i>	106	12	37 (35%)
<i>Wetland</i>	<i>Scrub Wetland</i>	16	0	4 (25%)
	<i>Open Wetland</i>	55	0	16 (29%)

Discussion

Based on this study and several other studies (Beck et al., 2011; Goetz et al., 2005; Verbyla, 2008), it is clear that a regional trend in declining NDVI has been occurring in interior Alaska boreal forests over the past 20-30 years. This study examined what areas of the boreal landscape are contributing to this regional trend. I focused on BCEF, where in a relatively small area (less 50 km²) there are a variety of landscape positions (uplands, floodplains, and lowlands), topographic positions (aspect and slope),

disturbances, and plant communities that are representative of interior Alaska boreal forests. We expected to see differences in NDVI trends based on these factors.

Study Area NDVI Trends

I analyzed remotely sensed Landsat imagery to identify long-term changes in forest productivity (NDVI) at the landscape-level. I found a negative trend in NDVI at BCEF over the years I examined (Table 3.3), which is consistent with previous research that examined NDVI trends throughout interior Alaska boreal forests (Goetz et al 2005; Verbyla 2008). The observed decline in NDVI coincides with rising temperature and a decrease in precipitation resulting in increased growing season length (Wendler et al., 2009) and drought stress (Barber et al., 2000).

Effect of landscape position on NDVI trends

There was a similar negative trend in NDVI in the uplands, lowlands, and floodplain (Figure 3.3 and Table 3.3). This was surprising as we expected to see a greater negative trend in NDVI in the uplands than the floodplains or lowlands due to difference in depth of the groundwater table and drainage (Van Cleve et al., 1996).

Recent work by Nossov et al. (2010), on the Tanana River Floodplain, where they examined annual radial growth suggests that riparian thinleaf alder growth is sensitive to drought stress early in the growing season and Yarie (2008) found that floodplain white spruce was sensitive to drought stress in a 16 year through fall exclusion experiment, which could explain the negative trend I observed in the floodplains. Based on tree-ring data, drought induced reduced growth in white spruce stands has occurred in all

landscape positions including the floodplains (Barber et al., 2000; Beck et al., 2011). Lowland black spruce stands with relatively good drainage have also shown a negative growth response, found by examining tree ring data, with increasing temperatures (Wilmking et al., 2008). Rich fens in BCEF lowlands that were subjected to experimental drought and warming exhibited decreased productivity (Chivers et al., 2009).

Mean NDVI had a high departure from the trend line in the year 2000 for each of the landscape positions (Figure 3.3). The increase in mean NDVI observed in each of the landscape positions in the year 2000 follows high total growing season (May-August) precipitation in 1998 (Western Region Climate Center, 2011) (Figure 3.12). Other peaks in total May-August precipitation in the years 1990 and 2003 were not followed by similar increases in NDVI. The unique feature of 1998 is that it was followed by three years of near average precipitation while 1990 and 2003 were followed by years of summer drought (Figure 3.12).

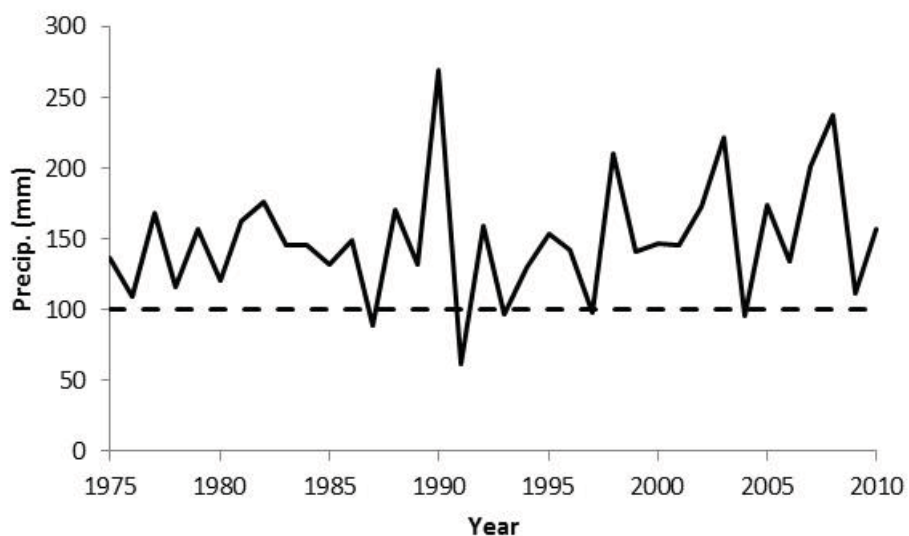


Figure 3.12 Total growing season (May-August) precipitation for the Fairbanks Airport.

Effects of topographic class on NDVI trends

The negative trend was similar on north and south facing slopes (Figure 3.4 and Table 3.3). Aspect is a key factor in vegetation distribution in interior Alaska due to the low sun angle which leads to differences in length of growing season, solar insolation, and soil temperature (Viereck et al., 1986). North facing slopes throughout BCEF are typically underlain by permafrost (Jorgenson et al., 2010) which limits drainage and should decrease drought stress therefore, we expected to see less of a negative NDVI trend on north facing slopes.

The NDVI declines I observed on north facing slopes may be due to factors other than drought stress however, black spruce, the dominant canopy species on north facing slopes throughout BCEF, has exhibited drought stress (Beck et al., 2011; Wilmking et al., 2008). The age of upland black spruce stands throughout BCEF is uniform (80-120 years) (Hollingsworth et al., 2006) and we may be observing an age-related decline in

above-ground productivity (Yarie et al., 2002). Regardless of the cause of declines in NDVI on north facing slopes is surprising considering the plasticity of black spruce, which is the most widespread stand type throughout the boreal forest of Alaska and western Canada (Viereck et al., 1992) and should therefore, be able to withstand environmental changes.

NDVI following wildfire

Two recent fires in BCEF provided an excellent opportunity to examine post fire NDVI trends where I observed an increase in NDVI following both fires (Figure 3.5). The Rosie Creek burn (1983) is succeeding to a broadleaf forest and NDVI values peaked about 17 years after the fire (Figure 3.5) which is consistent with observed increases in NDVI following fire (Epting et al., 2005). The NDVI trend in the area that burned in the Survey Line fire was similar to the adjacent lowlands prior to the fire, following the fire NDVI was dramatically reduced but rose sharply to return to levels similar to the adjacent lowlands (Figure 3.7).

The increase in NDVI in the Survey Line burn area was more pronounced than the increase in NDVI immediately following the Rosie Creek fire (Figure 3.5). The different recovery rates following these two fires may be due to differences in fire severity (Johnstone et al., 2010), pre-fire vegetation, and post fire organic layer depth which plays a role in re-sprouting potential, seed germination, and seedling establishment (Johnstone et al., 2006). The Survey Line burn area is a wet lowland area (Epting, 2005; Wilmking et al., 2008), while the Rosie Creek burn area is relatively well-drained and dry due to the south-facing intermediate slope it occurs on (Viereck et al., 1985). The pre-

fire vegetation of the Survey Line burn consisted of relatively low NDVI black spruce communities while some of the upland Rosie Creek burn was relatively high NDVI broadleaf forests. The 5-year recovery of NDVI in the Survey Line burn site may be the result of rapid re-sprouting of graminoids and broadleaf shrub establishment, while the Rosie Creek burn site did not recover until the establishment of broadleaf trees 17 years later.

Differences in NDVI between vegetation types

Examination of NDVI trends in different vegetation types gives us the opportunity to compare responses between broadleaf and conifer growing in similar landscape positions and topographic classes. For example, white spruce are typically considered late successional species as compared to birch but the two typically occur on similar sites in terms of slope, aspect, parent material, and drainage. Although species have different drought tolerances and are susceptible to different insect infestations I found similar negative trends in all of the plant communities examined. For instance, a comparison of birch and white spruce in the BCEF uplands shows a similar negative trend (Table 3.6 and Figure 3.10). These results are not consistent with previous research suggesting differences in drought-related productivity in deciduous vs. coniferous stands (Kljun et al., 2006; Welp et al., 2007).

There was a stronger negative NDVI response in floodplain vs. upland white spruce and mixed forests (Table 3.6 and Figure 3.8) which is consistent with Yarie (2008) who found a greater drought response in the floodplains than the uplands in a 16 year rain through fall exclusion experiment. A correlation matrix of the NDVI trends in upland

and floodplain white spruce and birch shows a strong correlation between upland and floodplain white spruce and between floodplain white spruce and birch (Table 3.7). The strong correlation between floodplain white spruce and birch, which occur primarily in the uplands, is surprising. If the negative NDVI trends are due to drought stress we would expect a stronger correlation between upland white spruce and birch vs. floodplain white spruce and birch. The reason for this expectation is that the upland white spruce and birch occur on similar upland sites and therefore the factors controlling soil moisture, such as precipitation, should be similar. On the other hand, factors controlling soil moisture on the glacially fed Tanana River Floodplain, such as glacial discharge, which increases with hot, dry weather, can be paradoxical upland factors (Nossov et al, 2010; Yarie, 2008).

Aspen did not exhibit a significant trend in NDVI (Table 3.6). The two outlier years, 1986 and 2006, were both years with relatively high counts of defoliating insects, and very low NDVI values (Figure 3.9). The year 1986 was a high aspen tortrix year and 2006 was a high aspen leaf miner year (Werner, 2010). The low NDVI values from these two years were so much lower than the trend line that the resulting variance in the data led to an insignificant p-value. However, when these years were excluded aspen exhibited a significant negative trend in NDVI (Figure 3.9).

Over half of the individual vegetation polygons exhibited a significant negative trend (Table 3.8). Most of the vegetation polygons that exhibited a significant positive trend were in floodplain early successional class (Table 3.8). As with the Rosie Creek and Survey Line burn areas we would expect to see an increase in NDVI in the floodplain

early successional class polygons due to increased colonization of alluvial bars. The acidic black spruce class had the highest percentage of negative trending polygons. This may be due to the tendency for this type to occur on slopes in the study area leading to drier conditions and drought stress as compared to the non-acidic black spruce which occurs mainly in moist lowlands throughout the study area.

Addressing potential bias due to sensor degradation

It was surprising to see such a consistent negative trend throughout the study area regardless of landscape position or vegetation type. While we can't be certain that this consistent trend is due to actual changes in vegetation productivity rather than sensor degradation an examination of several of my results supports the belief that the observed trends are indeed due to changes in vegetation productivity. The year 2004 was one of the warmest and driest summers in interior Alaska in 100 years (Wendler et al., 2010) Figure 3.1 shows a strong variance in response to the 2004 drought depending on vegetation type. This observed variance in response is consistent with the increased inter-annual variability in drought response in broadleaf deciduous vs. needle-leaf evergreen species (Arain et al., 2002). And consistent with observations of greater negative response to drought in aspen vs. black spruce using eddy covariance observations (Welp, 2007). Finally, the greater negative response observed in floodplain vs. upland white spruce (Figure 3.8 and Table 3.6) is consistent with the greater decrease in productivity in floodplain white spruce observed by Yarie (2008) in a 16 year rain through fall exclusion experiment in BCEF.

References

- Angert, A., Biraud, S., Bonfils, C., Henning, C. C., Buermann, W., Pinzon, J., Tucker, C. J., and Fung, I. 2005. "Drier summers cancel out the CO₂ uptake enhancement induced by warmer springs." *Proceedings of the National Academy of Sciences of the United States of America* no. 102 (31):10823-10827. doi: 10.1073/pnas.0501647102.
- Arain, M. A., Black, T. A., Barr, A. G., Jarvis, P. G., Massheder, J. M., Verseghy, D. L., and Nesic, Z. 2002. "Effects of seasonal and interannual climate variability on net ecosystem productivity of boreal deciduous and conifer forests." *Canadian Journal of Forest Research* no. 32 (5):878.
- Barber, V. A., Juday, G. P., and Finney, B. P. 2004. "Reconstruction of summer temperatures in interior Alaska from tree-ring proxies: evidence for changing synoptic climate regimes." *Climatic Change* no. 63:91-120.
- Barber, Valerie A., Juday, Glenn Patrick, and Finney, Bruce P. 2000. "Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress." *Nature* no. 405 (6787):668.
- Beck, P. S.A., Juday, G., Alix, C., Barber, V., Winslow, S., Sousa, E., Heiser, P., Herriges, J.D., and Goetz, S.J. 2011. "Changes in forest productivity across Alaska consistent with biome shift." *Ecology Letters* no. 14 (4):373-379.
- Bunn, A.G., Goetz, S.J., Fiske, and G.J. 2005. "Observed and predicted responses of plant growth to climate across Canada." *Geophysical Research Letters* no. 32.

- Cao, M. and Woodward, F.I. 1998. "Dynamic responses of terrestrial ecosystem carbon cycling to global climate change." *Nature* no. 393:249-.
- Chapin, F. S., III, McGuire, A. D., Ruess, R.W., Hollingsworth, T.N., Mack, M.C., Johnstone, J.F., Kasischke, E.S., Euskirchen, E.S., Jones, J.B., Jorgenson, M. T., Kielland, K., Kofinas, G.P., Turetsky, M.R., Yarie, J., Lloyd, A.H., and Taylor, D.L. 2010. "Resilience of Alaska's boreal forest to climatic change." *Canadian Journal of Forest Research* no. 40:1360-1370.
- Chapin, F. S., III, Oswood, M. W., Van Cleve, K., Viereck, L. A., and Verbyla, D. L. 2006. "Alaska's Changing Boreal Forest."
- Chivers, M.R., Turetsky, M.R., Waddington, J.M., Harden, J.W., and McGuire, A. D. 2009. "Effects of experimental water table and temperature manipulations on ecosystem CO₂ fluxes in an Alaskan rich fen." *Ecosystems* no. 12:1329-1342.
- Eissenstat, D.M., Wells, C.E., Yanai, R.D., and Whitbeck, J.L. 2000. "Building roots in a changing environment: implications for root longevity." *New Phytologist* no. 147 (1):33-42.
- Epting, J., and Verbyla, D. 2005. "Landscape-level interactions of prefire vegetation, burn severity, and postfire vegetation over a 16-year period in interior Alaska." *Canadian Journal of Forest Research* no. 35:1367-1377.
- Epting, Justin. 2005. "Evaluation of remotely sensed indices for assessing burn severity in the interior Alaska using Landsat TM and ETM+." *Remote Sensing of the Environment* no. 96 (3/4):328.

- Goetz, Scott J., Bunn, Andrew G., Fiske, Gregory J., and Houghton, R.A. 2005. "Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance." *PNAS* no. 102 (38):13521-13525.
- Hall, F.G., Strebel, D.E., Nickeson, J.E., and Goetz, S.J. 1991. "Radiometric rectification; toward a common radiometric response among multirate, multisensor images." *Remote Sensing of Environment* no. 35:11-27.
- Hammond, T. and Yarie, J. 1996. "Spatial prediction of climatic state factor regions in Alaska." *Ecoscience* no. 3 (4):490-501.
- Hansen, James, Sato, Makiko, Ruedy, Reto, Lo, Ken, Lea, David W., and Medina-Elizade, Martin. 2006. "Global temperature change." *PNAS* no. 103 (39):14288-14293.
- Hollingsworth, T.N., M.D. Walker, Chapin, F. S., III, and Parsons, A.L. 2006. "Scale-dependent environmental controls over species composition in Alaskan black spruce communities." *Canadian Journal of Forest Research* no. 36 (7):1781-1796.
- Jia, Gensuo J., Epstein, Howard E., and Walker, Donald A. 2003. "Greening of arctic Alaska, 1981-2001
" *Geophysical Research Letters* no. 30 (20):3.
- Johnstone, J.F. and Chapin, F. S., III 2006. "Effects of soil burn severity on post-fire tree recruitment in boreal forest." *Ecosystems* no. 9:14-31.

- Johnstone, J.F., Chapin, F. S., III, Hollingsworth, T.N., Mack, M.C., Romanovsky, V.E., and Turetsky, M.R. 2010. "Fire, climate change, and forest resilience in interior Alaska." *Canadian Journal of Forest Research* no. 40:1302-1312.
- Jorgenson, M. T., Romanovsky, V.E., Harden, J.W., Shur, Y., O'Donnell, J., Schuur, E.A.G., Kanevskiy, M.E., Alexander, and Marchenko, S. 2010. "Resilience and vulnerability of permafrost to climate change." *Canadian Journal of Forest Research* no. 40:1219-1236.
- Kasischke, E., Verbyla, D., Rupp, S., McGuire, A. D., Murphy, K., Jandt, R., Barnes, J.L., Hoy, E.E., Duffy, P.A., Calef, M., and Turetsky, M.R. 2010. "Alaska's changing fire regime-implications for the vulnerability of its boreal forests." *Canadian Journal of Forest Research* no. 40:1313-1324.
- Kljun, N., Black, T., Griffis, T., Barr, A., Gaumont-Guay, D., Morgenstern, K., McCaughey, J., and Nesic, Z. 2006. "Response of net ecosystem productivity of three boreal forest stands to drought." *Ecosystems* no. 9 (7):1128.
- Michaelian, M., Hogg, E.H., Hall, R.J., and Arsenault, E. 2011. "Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest." *Global Change Biology* no. 17:2084-2094.
- Myneni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G., and Nemani, R.R. 1997. "Increased plant growth in the northern high latitudes from 1981 to 1991." *Nature* no. 386:698-.
- Nagel, D. 2007. Comparison of two models for identifying low gradient, unconfined streams and valley bottom extent: In support of stream temperature modeling

associated with fire effects. USDA Forest Service, Rocky Mountain Research Station, Boise Aquatic Sciences Laboratory.

Nossov, D.R., Ruess, R.W., and Hollingsworth, T.N. 2010. "Climate sensitivity of thinleaf alder growth on an interior Alaskan floodplain." *Ecoscience* no. 17 (3):312-320.

Parent, M.B. and Verbyla, D. 2010. "The browning of Alaska's boreal forest." *Remote Sensing* no. 2:2729-2747.

Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.M., Tucker, C.J., and Stenseth, N. C. 2005. "Using the satellite-derived NDVI to assess ecological responses to environmental change." *Trends in Ecology and Evolution* no. 20 (9):503-510.

Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G. Y., and Solomon, S. 2001. "Radiative forcing of climate change." In *Climate Change 2001: The Scientific Basis* edited by Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M, van der Linden, P.J., Dai, X., Maskell, K., Johnson and C.A., 349-416. Cambridge University Press.

Richmond, M.A. and Shy, T.L. 2005. An extraordinary summer in the interior of Alaska. Paper read at 85th AMS Meeting, 9-13 January, at San Diego, CA.

Schimel, J.P., and Chapin, F. S., III 2006. "Microbial processes in the Alaska boreal forest." In *Alaska's Changing Boreal Forest*, edited by Chapin III, F.S., Oswood, M. W., Van Cleve, K., Viereck, L. A., Verbyla and D., 227-240. New York: Oxford University Press.

- Soja, Amber J., Tchebakova, Nadezda M., French, Nancy H. F., Flannigan, Michael D., Shugart, Herman H., Stocks, Brian J., Sukhinin, Anatoly I., Parfenova, E. I., Chapin, F. S., III, and Stackhouse, Paul W. Jr. 2007. "Climate-induced boreal forest change: Predictions versus current observations." *Global and Planetary Change* no. 56 (3-4):274.
- Stafford, J. M., Wendler, G., and Curtis, J. 2000. "Temperature and precipitation of Alaska: 50 year trend analysis." *Theoretical and Applied Climatology* no. 67 (1):33.
- U.S. Department of the Interior, Bureau of Land Management. 2010. Wildland Fire Dataset for Alaska.
- Van Cleve, K., Viereck, L. A., and Dyrness, C.T. 1996. "State factor control of soils and forest succession along the Tanana River in interior Alaska." *Arctic and Alpine Research* no. 28 (3):388-400.
- Verbyla, D. 2008. "The greening and browning of Alaska based on 1982-2003 data." *Global Ecology and Biogeography* no. 17:547-555.
- Viereck, L. A., Van Cleve, K., and Dyrness, C.T. 1986. "Forest ecosystem distribution in the taiga environment." In *Forest Ecosystems in the Alaskan Taiga: A synthesis of structure and function*, edited by Van Cleve, K., Chapin III, F. S., Flanagan and L.A., 22-43. New York: Springer-Verlag.
- Viereck, L. A., Dyrness, C.T., Batten, A.R., and Wenzlick, K.J. 1992. *Alaska Vegetation Classification*. USDA Forest Service, General Technical Report.

- Viereck, L. A., Dyrness, C.T., and Foote, M.J. 1993. "An overview of the vegetation and soils of the floodplain ecosystems of the Tanana River, interior Alaska." *Canadian Journal of Forest Research* no. 23:889-898.
- Viereck, L. A. and Foote, M.J. 1985. "Effects of the Rosie Creek Fire on selected environmental factors in Bonanza Creek Experimental Forest." In *Early Results of the Rosie Creek Fire Research Project*, edited by Juday, G. P., Dyrness and C.T. Fairbanks, AK: University of Alaska Fairbanks.
- Volney, W. Jan A., and Fleming, Richard A. 2000. "Climate change and impacts of boreal forest insects." *Agriculture, Ecosystems & Environment* no. 82 (1-3):283.
- Welp, L. R., Randerson, J. T., and Liu, H. P. 2007. "The sensitivity of carbon fluxes to spring warming and summer drought depends on plant functional type in boreal forest ecosystems." *Agricultural and Forest Meteorology* no. 147 (3-4):172.
- Wendler, G., Conner, J., Moore, B., Shulski, M.E., and Stuefer, M. 2010. "Climatology of Alaskan wildfires with special emphasis on the extreme year of 2004." *Theoretical and Applied Climatology* no. Online First.
- Wendler, Gerd and Shulski, Martha. 2009. "A Century of Climate Change for Fairbanks, Alaska." *Arctic* no. 62 (3):295.
- Werner, R. 2010. Bonanza Creek Experimental Forest defoliating insect population levels per leaf beginning 1975. edited by Bonanza Creek LTER. Fairbanks, AK.
- Western Regional Climate Center. 2011. Fairbanks WSO Airport, Alaska: monthly total precipitation (inches). edited by Western Regional Climate Center. Reno.

Wilmking, M. and Myers-Smith, Isla. 2008. "Changing climate sensitivity of black spruce (*Picea mariana* Mill.) in a peatland-forest landscape in Interior Alaska."

Dendrochronologia no. 25:167-175.

Yarie, J. and Billings, S. 2002. "Carbon balance of the taiga forest within Alaska: present and future." *Canadian Journal of Forest Research* no. 32:757-767.

Chapter 4 General Conclusions

It is clear that climate is changing in interior Alaska (Wendler et al., 2009) and that these changes are affecting vegetation productivity (Barber et al. 2000; Beck et al., 2011; McGuire et al. 2010). I found negative trends in a remotely sensed vegetation index (NDVI) at several spatial scales of landscape position, topographic class, and plant community type. While this work was done on a small scale the consistency of the trends in my work with similar studies indicates changes that can possibly be scaled up to the broader interior Alaska boreal forest. Given the vastness of the boreal forest and the potential feedbacks on climate in terms of carbon sequestration and storage it is crucial to monitor changes and disentangle the mechanisms of change in plant productivity to better be able to predict outcomes and prepare for them.

Drought stress related declines in vegetation productivity have been observed by many studies throughout the interior Alaska boreal forest landscape (Barber et al. 2000; McGuire et al. 2010). While some of the trends I observed were surprising such as similar decreases on north and south facing slopes and decreasing trends in all of the plant communities examined there are other field based studies that have observed drought stress related declines in most of the communities examined such as black spruce (Wilmking et al. 2008), white spruce (McGuire et al. 2010), and aspen (Michaelian et al. 2011). There are also other factors such as age-related declines in productivity that may be contributing to the observed trends. While all of the plant communities observed exhibited a negative trend there is evidence of a stronger negative trend in mid to late successional stands in the floodplain as compared to analogous stands in the uplands,

which is consistent with the trend observed by Yarie (2008) in his 16 year rain exclusion experiment in BCEF upland and floodplain white spruce communities.

The overall trend within the entire study area was similar to observations by other studies looking at NDVI trends in interior Alaska boreal forests (Beck et al. 2011; Goetz et al. 2005; Parent et al. 2010; Verbyla, 2008), and consistent with an increasing frequency of drought in the region (Wendler et al., 2009). In addition the increasing trend following the two recent fires in BCEF is consistent with other studies (Epting, 2005).

NDVI is a useful tool for monitoring vegetation response to climate change and the story will only become more interesting as the climate is projected to continue warming and years of NDVI data continue to be acquired. My study provides a useful model for continued monitoring of future NDVI trends throughout BCEF.

References

- Barber, Valerie A., Juday, Glenn Patrick, and Finney, Bruce P. 2000. "Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress." *Nature* no. 405 (6787):668.
- Beck, P. S.A., Juday, G., Alix, C., Barber, V., Winslow, S., Sousa, E., Heiser, P., Herriges, J.D., and Goetz, S.J. 2011. "Changes in forest productivity across Alaska consistent with biome shift." *Ecology Letters* no. 14 (4):373-379.
- Epting, Justin. 2005. "Evaluation of remotely sensed indices for assessing burn severity in the interior Alaska using Landsat TM and ETM+." *Remote Sensing of the Environment* no. 96 (3/4):328.
- Goetz, Scott J., Bunn, Andrew G., Fiske, Gregory J., and Houghton, R.A. 2005. "Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance." *PNAS* no. 102 (38):13521-13525.
- Kljun, N., Black, T., Griffis, T., Barr, A., Gaumont-Guay, D., Morgenstern, K., McCaughey, J., and Nesic, Z. 2006. "Response of Net Ecosystem Productivity of Three Boreal Forest Stands to Drought." *Ecosystems* no. 9 (7):1128.
- McGuire, A. D., Ruess, R.W., Lloyd, A.H., Yarie, J., Klein, J., and Juday, G. 2010. "Vulnerability of white spruce tree growth in interior Alaska in response to climate variability: dendrochronological, demographic, and experimental perspectives." *Canadian Journal of Forest Research* no. 40:1197-1209.

- Michaelian, M., Hogg, E.H., Hall, R.J., and Arsenault, E. 2011. "Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest." *Global Change Biology* no. 17:2084-2094.
- Nossov, D.R., Ruess, R.W., and Hollingsworth, T.N. 2010. "Climate sensitivity of thinleaf alder growth on an interior Alaskan floodplain." *Ecoscience* no. 17 (3):312-320.
- Parent, M.B. and Verbyla, D. 2010. "The browning of Alaska's boreal forest." *Remote Sensing* no. 2:2729-2747.
- Verbyla, D. 2008. "The greening and browning of Alaska based on 1982-2003 data." *Global Ecology and Biogeography* no. 17:547-555.
- Wendler, Gerd and Shulski, Martha. 2009. "A Century of Climate Change for Fairbanks, Alaska." *Arctic* no. 62 (3):295.
- Wilmking, M. and Myers-Smith, Isla. 2008. "Changing climate sensitivity of black spruce (*Picea mariana* Mill.) in a peatland-forest landscape in Interior Alaska." *Dendrochronologia* no. 25:167-175.
- Yarie, J. 2008. "Effects of moisture limitation on tree growth in upland and floodplain forest ecosystems in interior Alaska." *Forest Ecology and Management* no. 256:1055-1063.