THE BOREAL FOREST OF INTERIOR ALASKA: PATTERNS, SCALES, AND CLIMATE CHANGE

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Abstract

According to a variety of field observations, most forest types of the boreal forest in Interior Alaska can be found at unique elevation ranges and topographic slopes and aspects. My analysis of spatial interactions among fire, vegetation type, and topography at 1km resolution suggests that these spatial patterns are still represented at this scale.

In order to understand drivers of vegetation type distribution and change, a hierarchical logistic regression model was developed. The model indicates that the distinction between tundra versus forest is driven by elevation, precipitation, and south to north aspect. The separation between deciduous forest versus spruce forest is driven by fire interval and elevation. The identification of black versus white spruce uses fire interval and elevation as the main drivers. The model was validated in Interior Alaska and Northwest Canada where it could predict vegetation with good accuracy. The logistic regression model could also be used to distinguish bog vegetation from all other vegetation types and improved in predictive ability when actual fire history was included in model development.

The model was then used to identify vegetation response to environmental change by imposing changes in temperature, precipitation, and fire interval. Black spruce remains the dominant vegetation type under all scenarios expanding most under warming coupled with increasing fire interval. White spruce is clearly limited by moisture once average growing season temperatures exceed 2°C. Deciduous forests expand their range the most when decreasing fire interval, warming, and increasing precipitation are combined. Tundra is replaced by forest under warming but expands under precipitation

increase. Model predictions agree with current knowledge of the response of vegetation types to climate change. The response of vegetation types to environmental changes is not linear when two changes are imposed simultaneously.

The last chapter explores the compatibility and accuracy of currently existing classifications for Interior Alaska and the effect of scale. Overall agreement among the classifications is very low; low kappa values indicate that much of the agreement among the classifications can be attributed to random chance. The resolution of the vegetation classifications affects the representation of vegetation types: the major vegetation types eliminate the less abundant types with increasing coarseness.

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Dedication Page

I want to dedicate this dissertation to my husband Fred and my family who never stopped believing and supporting me through all these years of higher education. This dissertation would not have been possibly without my advisors Hank Shugart and Howie Epstein. Thank you for your patience, Howie and helping me in so many ways, I wouldn't have made it without you. Thank you also to my committee members Wallace Reed and Laura Galloway for their constructive criticism and faith that I could finish long distance. I am very grateful to Dave McGuire, Scott Rupp, Terry Chapin, and Jill Johnstone who not only welcomed me to Alaska but also patiently listened to my ideas and worked their way through tedious early drafts. Thank you!

Chapter 1 – Introduction to the boreal forest

The high latitude biomes of tundra and boreal forest cover approximately 25% of the Earth's terrestrial environment (Apps *et al.* 1993). Their boundaries can be defined by several characteristics of soil, climate, and vegetation. The arctic and sub-arctic form a uniform belt around the North Pole and their large extents cover several continents. The arctic is loosely defined by the Arctic Circle at 66°32'N; however, this exact latitude has no direct ecological significance (Stonehouse 1989). The sub-arctic environment is very similar to the actual arctic, though temperatures become increasingly milder towards the south. The high latitude environment is characterized by very low sun angles, a long polar winter (no sun), a long polar summer (no sun set), and low average temperatures (Stonehouse 1989). Köppen and Geiger (1936) defined the polar region by a polar climate criterion, which requires that the mean temperature of every month is less than 10°C. In the northern hemisphere, this isotherm also approximates the treeline (within 100 to 200 km) (Stonehouse 1989). One important characteristic of the arctic is the presence of permafrost, which can be continuous or discontinuous and has significant impact on plant growth and litter decomposition. When the uppermost soil layer thaws in the summer, ground infiltration by water is prevented by the underlying permafrost barrier resulting in waterlogged or flooded soil conditions (Stonehouse 1989). This flooded, anaerobic situation controls litter decomposition rates and thus release of methane and carbon dioxide (Lashof 1989). This leads to the paradox of high latitudes where soil moisture is extremely high even though precipitation is minimal. Another characteristic of these northern ecosystems is peat accumulation in the soil, which currently functions as a major carbon store (Billings *et al.* 1982, Whalen and Reeburgh 1988, Whalen and Reeburgh 1990, Christensen 1991). Peat accumulation is a result of very slow decomposition due to low ambient temperatures and waterlogged conditions. Whalen and Reeburgh (1988) state that despite very slow primary production in arctic ecosystems, they store as much carbon as tropical forests.

Boreal forest or taiga refers to the sub polar coniferous forest that forms a circumpolar belt covering northern North America and Eurasia. This belt spans over 20° latitude, covers approximately 11% of the Earth's terrestrial surface and contains significant amounts of carbon in its soil (Barbour *et al.* 1987, Bonan and Shugart 1989, Apps *et al.* 1993). The taiga is characterized by relatively few species of modestly sized trees and a dense understory of lichen, moss and vascular plants. Mean temperature is above 10°C for 30 to 120 days at the northern and southern limits, respectively (Barbour *et al.* 1987). In North America, boreal forest extends across Alaska and most of Canada and dips into the Great Lakes states and New England to about 45° latitude (Barbour *et al.* 1987). Boreal forests are frequently disturbed by large-scale intense fires and catastrophic insect infestations (Wein and MacLean 1983, Payette 1992). There are strong connections among the permafrost table, ground cover, and disturbance by fire (Viereck 1983). Fire plays an important role in removing ground cover and forest floor litter and by blackening the ground. Solar radiation can then penetrate deeper into the soil, which allows deeper thawing, a decrease in soil moisture, and an increase in soil temperature (Brown 1983). Fire also makes nutrients available and creates open ground where seedlings can establish themselves (Viereck 1983).

Alaska is dominated by boreal forest which covers approximately 60% to 70% of the state (Van Cleve *et al.* 1983). The boreal zone of Alaska is flanked by the Brooks Range mountains in the North, the coastal tundra in the West, the Alaska Range in the South, and extends into Canada to the East. The forest is characterized by four major plant community types: black spruce, white spruce, deciduous forest, and bog (Viereck *et al.* 1983, Van Cleve *et al.* 1983, Yarie and Van Cleve 1983, Viereck *et al.* 1986, Szeicz and MacDonald 1995, Van Cleve *et al.* 1996). Black spruce (*Picea mariana*) and moss forests dominate on cold and poorly drained sites located on north-facing slopes, lowlands, and lower slopes. Black spruce is the most widespread forest type and is usually associated with permafrost. After a severe fire on a black spruce site, regrowth consists of herbs, which are gradually replaced by grasses, followed by shrubs, deciduous trees, and spruce saplings. On a permafrost black spruce site, it takes approximately 50 years until the establishment of a dense black spruce/moss forest which is replaced by mature black spruce forest after 100 years. White spruce (*Picea glauca*) is found on warm and dry south-facing upland sites and at the treeline. On upland white spruce sites the successional sequence is very similar to upland black spruce sites except there is more hardwood present. Twenty-five years after the fire, a dense hardwood stage consisting of birch and aspen can be found. Fifty years after the fire a mature hardwood stage is reached which is replaced by a mixed white spruce-hardwood stage after 100 years. The mature white spruce/moss stage is reached 200 years after an initial fire. Dry sites and active floodplains can also support deciduous forest containing paper birch (*Betula papyrifera),* quaking aspen (*Populus tremuloides),* and balsam poplar (*Populus balsamifera*). Very wet sites allow the growth of tamarack (*Larix laricina*). In the absence of fire, a boreal forest stand becomes increasingly cold and wet and can turn into a bog (Glebov and Korzukhin 1992).

Depending on site conditions and time since the last fire, tree density in the forest can vary from dense stands (Barbour *et al.* 1987) to open woodlands. Black spruce is much more prone to fire than white spruce or deciduous stands (Burns and Honkala 1990). Average fire cycles for black spruce stands range from 80-90 years in the MacKenzie Valley in Canada (Rowe *et al.* 1974) to 100 years for closed spruce in Alaska (Heinselman 1981). Open spruce-lichen forests have mean fire cycles of 130 years (Heinselman 1981) compared to 300 years for alluvial white spruce sites (Rowe *et al.* 1974).

Since the late 19th century, global surface temperatures have increased by 0.3 to 0.6ºC (Nicholls *et al.* 1996). This recent warming has been greatest over the continents between 40º and 70ºN. Mean precipitation has also increased globally by 1% despite precipitation decrease in the subtropics and tropics (Nicholls *et al.* 1996). Precipitation has mostly increased at high latitudes of the Northern Hemisphere, especially during the cold season, while the growing season has been extended into the spring and fall. Average air temperature in Fairbanks has increased by approximately 1°C between 1906 and 2001 (http://climate.gi.alaska.edu). Historically, high latitude ecosystems have been a net carbon sink because low temperatures and waterlogged conditions inhibited decomposition. Considering the vast amounts of carbon stored in these systems, climate change at high latitudes will significantly affect the global carbon budget (Kasischke 2000). There are also potential feedbacks between the boreal forest and the global climate (Bonan *et al.* 1992, Foley *et al.* 1994).

High-latitude warming can affect boreal forests in interior Alaska in three ways. Milder winters and longer growing seasons will directly affect vegetation growth. Warmer ambient temperatures change permafrost dynamics, which leads to deeper active layers and a different hydrological regime. Finally, changes in ambient temperatures and precipitation patterns can have a direct effect on fire frequency (Bergeron and Archambault 1993, Kasischke and Stocks 2000, Serreze *et al.* 2000). However, it is not perfectly understood how fire affects boreal forest dynamics, let alone how climate change will alter the system and what possible global feedbacks we can expect.

This dissertation explores issues regarding patterns among topography, vegetation, fire, and climate in the boreal forest of Interior Alaska and the effect of the scale of observation on these patterns. The second chapter investigates the relationships among topography, fire, and vegetation at $1km^2$ resolution. Topography dictates the distribution of vegetation types on the landscape. Since flammability differs among the stand types, the distribution of fire scars is indirectly related to topography. The third chapter introduces a logistic regression model that simulates the occurrence of the five major vegetation types: black spruce forest, white spruce forest, deciduous forest, tundra, and bog in Interior Alaska. Model inputs are: topography (elevation, aspect, slope), average growing season temperature, total growing season precipitation, drainage type, and fire return interval. The model is tested statistically and validated in Interior Alaska as well as western Canada. Logistic regression produces t and p statistics which identify drivers for vegetation types. In the fourth chapter, the logistic regression model is applied to simulate the response of the four major vegetation types (black spruce forest, white spruce forest, deciduous forest, and tundra) to climate changes. The model inputs (average growing season temperature, total growing season precipitation, and fire interval) are altered to represent climate change scenarios. Potential vegetation distribution in Interior Alaska for the year 2100 is simulated using the Hadley CM2 (Johns *et al*. 1997) climate change scenario. The fifth chapter assesses compatibility and accuracy of four currently available land cover classifications for Interior Alaska. The effect of scale on representation of vegetation types in a land cover classification is analyzed. There seems to be a gap between classifications currently available from remote sensing and classification requirements for vegetation modeling. This is followed by a chapter of conclusions.

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Chapter 2 - Fire and Vegetation Patterns

2.1 Abstract

According to a variety of field observations, most forest types of the boreal forest in Interior Alaska can be found at unique elevation ranges and topographic slopes and aspects. The boreal forest is also characterized by recurring disturbances such as wildfires and insect infestations which interrupt succession. The goal of this chapter was to investigate spatial interactions among fire, vegetation type, and topography at 1km resolution. Topographic information (elevation, aspect, and slope) was extracted from a 1km-resolution digital elevation model and overlaid with the USGS Global Land Cover Characteristics Database and the Alaska Fire Scar Database. Most fires occurred at low elevations and low slope angles where vegetation was dominated by spruce forest. Of the fires from 1993 to 1999, 80% occurred in spruce forest or spruce woodland, while only 9% occurred in deciduous forest. The analysis suggests that the spatial patterns among vegetation type, topography, and fire detected at local scales are still represented at a 1km resolution.

2.2 Introduction

Boreal forests form a circumpolar belt spanning over 20° latitude covering North America and northern Eurasia and containing one of the largest carbon reserves in the world (Post *et al.* 1982, Barbour *et al.* 1987, Apps *et al.* 1993). There are multiple indications from sea ice, glaciers, permafrost, and vegetation that Alaska is experiencing the effects of warmer temperatures and increased precipitation (Nicholls *et al.* 1996, Myneni *et al.* 1997, Briffa *et al.* 1998, Serreze *et al.* 2000, Keyser *et al.* 2000, Jorgensen *et al.* 2001). Considering the vast amounts of carbon stored in the boreal forest, consequences of climate change at high latitudes will significantly affect the global carbon budget with potentially important feedbacks between the boreal forest and the global climate (Foley *et al.* 1994, Eugster *et al.* 2000, Chapin *et al.* 2000).

The boreal forest is composed of relatively few species of modestly sized trees and a dense understory of lichen, moss, and vascular plants (Barbour *et al.* 1987). Boreal forest extends through the central part of Alaska, covering 60% to 70% of the state and continue through Canada to the east (Van Cleve *et al.* 1983). Topography plays an important role in this temperature-limited environment and determines succession and climax communities (Van Cleve *et al.* 1991). Three major forest community types can be distinguished: black spruce type, white spruce type, and deciduous forest. Bogs are found throughout the forest, while higher elevations are covered by tundra. The relationship between topography and vegetation in Alaska has been well described in the literature (Viereck *et al.* 1983, Van Cleve *et al.* 1983, Yarie and Van Cleve 1983, Van Cleve *et al.* 1986, Viereck *et al.* 1986, Van Cleve *et al.* 1996): Black spruce (*Picea mariana*) and moss forests dominate on cold and poorly drained sites located on north-facing slopes, lowlands, and lower slopes. Black spruce is the most widespread forest type and is associated with permafrost. Tamarack (*Larix laricina*) can also be found on very wet sites. Warm and dry south-facing upland sites as well as the tree line are typically dominated by white spruce (*Picea glauca)*. Dry sites can also support deciduous tree species such as paper birch (*Betula papyrifera)*, quaking aspen (*Populus tremuloides)*, and balsam poplar (*Populus balsamifera)*. Depending on site conditions and time since the last fire, tree density in the forest can vary from a dense stand to open lichen woodland. Active floodplains where permafrost is absent support productive forests of balsam poplar and white spruce.

The boreal forest of Interior Alaska is a disturbance forest that evolved under the influence of fire. Natural fire cycles in the boreal forest of northwest North America range from 60 (Yarie 1979) to 100 (Heinselman 1981) years for black spruce forest and 300 years (Rowe *et al.* 1974) for alluvial white spruce (Payette 1992). Fire plays an important role in system processes by removing ground cover and forest floor litter, and by blackening the ground (Viereck 1983). Solar heat flux can then penetrate deeper into the soil which allows deeper thawing, a decrease in soil moisture, and an increase in soil temperature (Dyrness and Norum 1983). Fire also makes nutrients available and creates open ground where seedlings can establish themselves (Zasada *et al.* 1987). In the absence of fire, a boreal forest stand becomes increasingly cold and wet and can possibly turn into a bog (Viereck et al. 1986).

After a severe fire in the boreal forest, herbs establish themselves and are gradually replaced by grasses, followed by shrubs, deciduous trees, and spruce saplings.

On a permafrost black spruce site, it takes approximately 50 years until the establishment of a dense black spruce/moss forest which is replaced by mature black spruce forest after 100 years. On upland white spruce sites the successional sequence is very similar except there is more hardwood present. Twenty-five years after the fire, a dense hardwood stage consisting of birch and aspen can be found. Fifty years after the fire a mature hardwood stage is reached which is replaced by a mixed white spruce-hardwood stage after roughly 100 years. The mature white spruce/moss stage is reached approximately 200 years after the initial fire (Van Cleve *et al.* 1986).

Understanding and predicting the complex dynamics of boreal forest and climate interactions requires the development of simulation models. These models can be created at various scales ranging from global to stand-level. A detailed landscape classification is a key requirement for plant community modeling. Due to the vastness and inaccessibility of the boreal forest, many modelers of this system rely on remotely sensed data. One very commonly used data set is the $1km^2$ resolution AVHRR (Advanced Very High Resolution Radiometer) dataset from NOAA satellites and various derivatives of it. Seemingly, the best forest classification currently available is the 1km-resolution North America land cover database developed from 1-km AVHRR data spanning April 1992 through March 1993 (Loveland *et al.* 1999). However, topography plays a very important role in this cold environment, and $1km^2$ pixel sizes might be too coarse to provide a clear representation of landscape patterns.

The goal of this paper is to explore three questions relevant to boreal forest modeling:

1. Are the patterns of vegetation types and topography (elevation, slope, and aspect) observed at the stand level retained at a 1km resolution?
2. At a 1km resolution, is the location of fire scars linked to topography?
3. Is the occurrence of large-scale fires correlated with vegetation types?

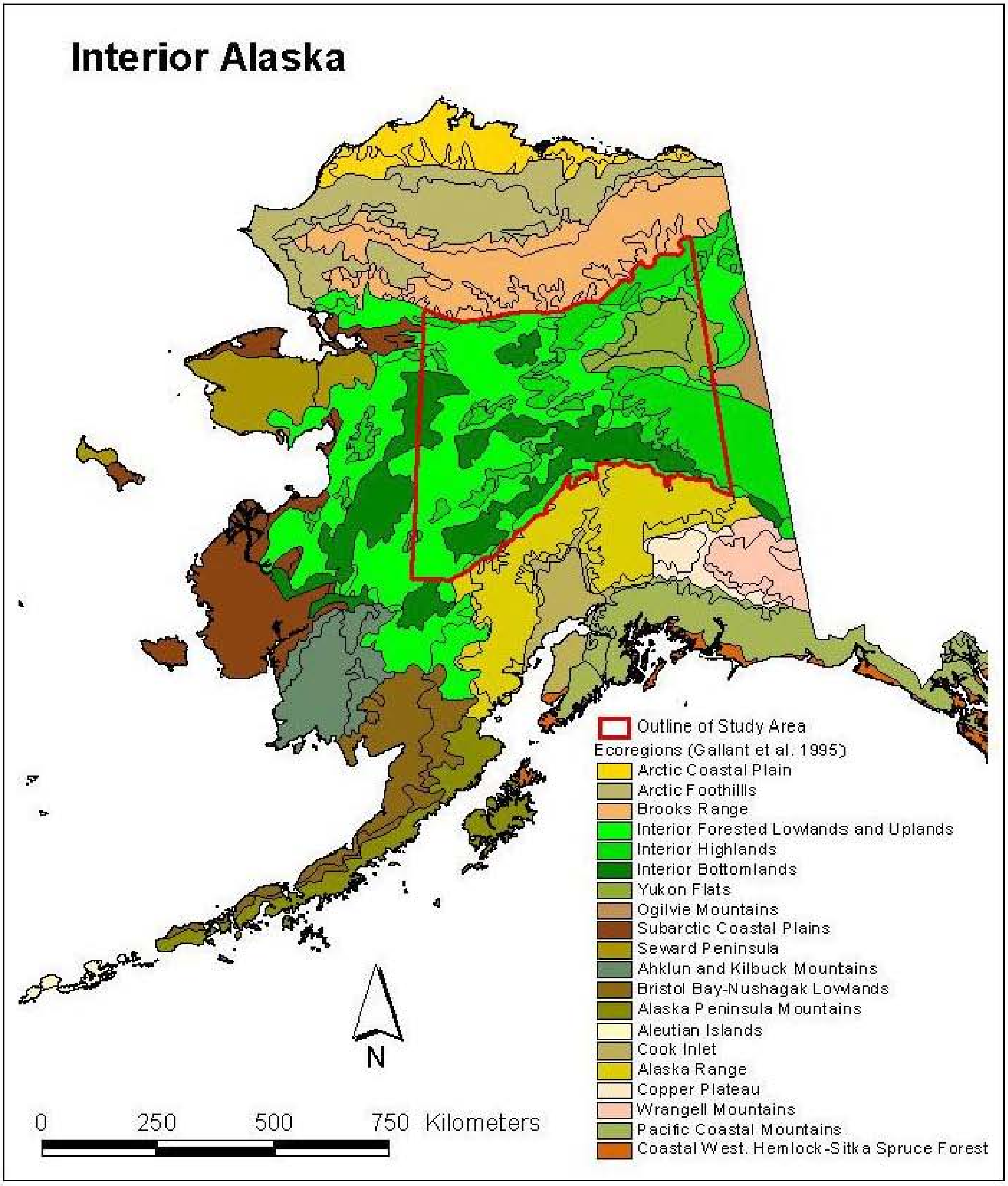
These questions were analyzed by overlaying and comparing a digital elevation model (DEM), the USGS classification (Loveland *et al.* 1999), and the Alaska Fire Scar Database in Interior Alaska.

2.3 Methods

The boundary of Interior Alaska for the purpose of this study was based on the four primary ecoregion types of central Alaska from the Ecoregion Dataset (Gallant *et al.* 1995): 'Interior Forested Lowland and Uplands,' 'Interior Highlands,' 'Interior Bottomlands,' and 'Yukon Flats' (Figure 2.1). To simplify the eastern and western extent of the study region and avoid non-Interior vegetation classes along the coast and the Canadian border, a straight north-to-south line was drawn on both sides. The total study area encompasses roughly 300,000km^2. From here on 'Interior Alaska' will be used synonymously with 'study region' even though actual Interior Alaska might be slightly larger. The topographic factors (elevation, aspect, and slope) were derived from a 1km-resolution U.S. Geological Survey (USGS) digital elevation model (DEM). The topographic factors were then reclassified to 100m increment elevation classes, 16 aspect classes, and 5% increment slope classes. To answer the question regarding vegetation and topography, the AVHRR-based, 1km resolution USGS North American Land Cover Characteristics Database (Loveland *et al.* 1999) was overlaid with slope, aspect, and elevation and analyzed for patterns within the new, combined classes. To analyze the influence of topography on fire, fire information was taken from the Alaska Fire Scar Database from the Alaska Fire Service (Murphy *et al.* 2000)) which contains the polygon outlines of fires from 1950 to 1999. Area burnt for each year was extracted, converted to 1km-resolution grids, and then overlaid with elevation, aspect, and slope. To understand more about the relationship between vegetation and fire, the vegetation data set was overlaid with the fire data set.

Fire cycle is defined as the number of years required to burn an area equal to the size of the study area (Johnson 1992). This definition was applied here to calculate a theoretical fire cycle as: Fire $cycle_{category}$ = the number of years required to burn the entire area of this particular category; where the category could be a vegetation type or a topographic class.

Figure 2.1 Delineation of Interior Alaska



2.4 Results

2.4.1 Interior Alaskan Topography

The topography of Interior Alaska is not distributed evenly but is dominated by:

- 100m to 300m elevations which make up 53% of the landscape,
- W to N aspects, which make up 45% of the landscape, and
- 0 to 5% slopes, which make up 64% of the landscape (Figure 2.2).

This skews any analysis simply by area, since for example most of the fires may occur in the topographic classes that are most common on the landscape. To offset this, most findings were normalized by total area in each respective vegetation class or topographic combination.

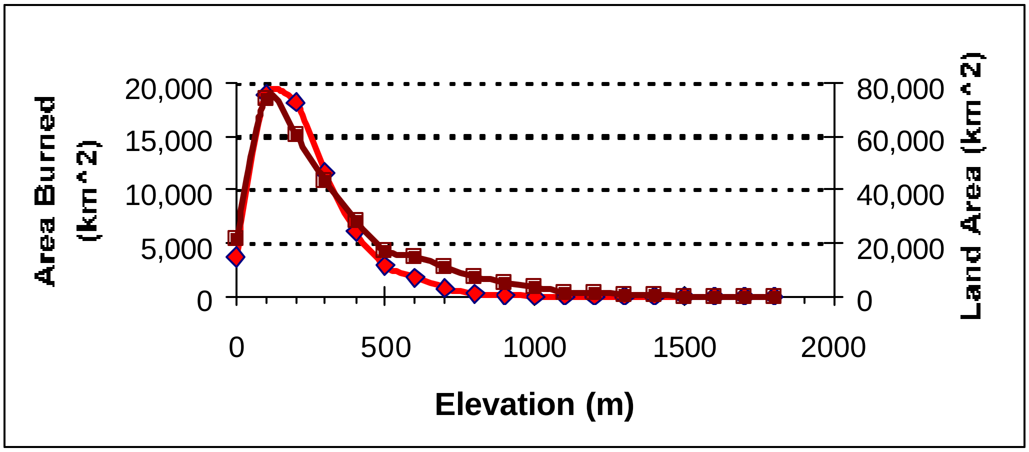
2.4.2 Vegetation Distribution in Interior Alaska

The land cover data set for Alaska contains 38 categories (including water) in Interior Alaska (Table 1). However, 70% of the entire study area is covered by only four vegetation classes: 'White, black spruce forest' (29% of the total area), 'Black spruce, tamarack, lichen woodland' (17%), 'Deciduous forest and tall shrubs' (17%), and 'Spruce woodlands and shrub bogs' (7%).

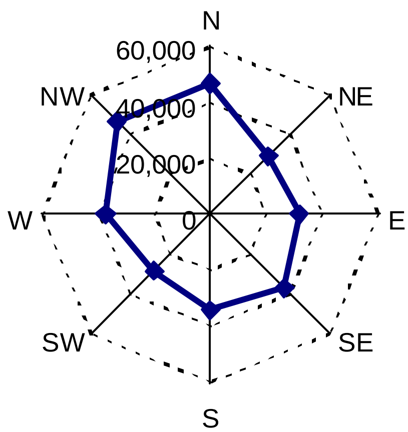
These four major vegetation classes clearly show preferences for different elevation ranges (Figure 2.3). Arranging vegetation classes by aspect displays patterns, especially when vegetation classes are simultaneously grouped by elevation (Figure 2.4).

Figure 2.2 Topography and fire in Interior Alaska

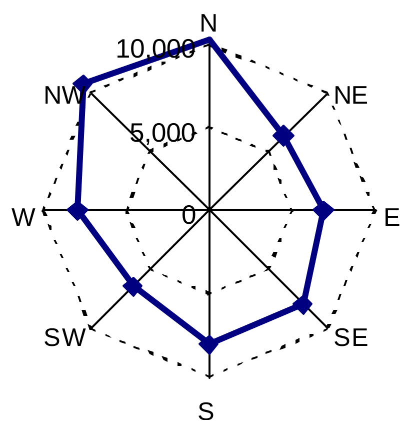
Distribution of area burned (diamonds) and total land area (squares) (in km^2) by elevation



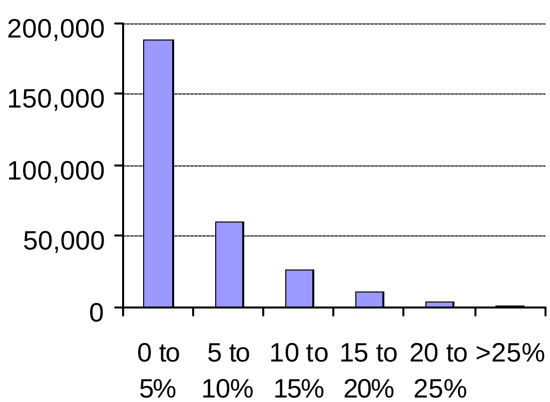
Land area (km^2) by aspect



Area burned (km^2) by aspect



Land area (km^2) by slope class



Area burned (km^2) by slope class

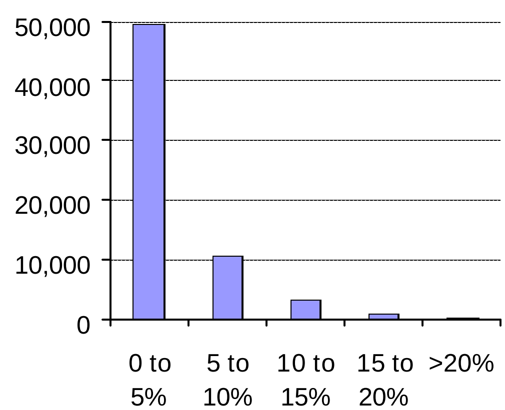


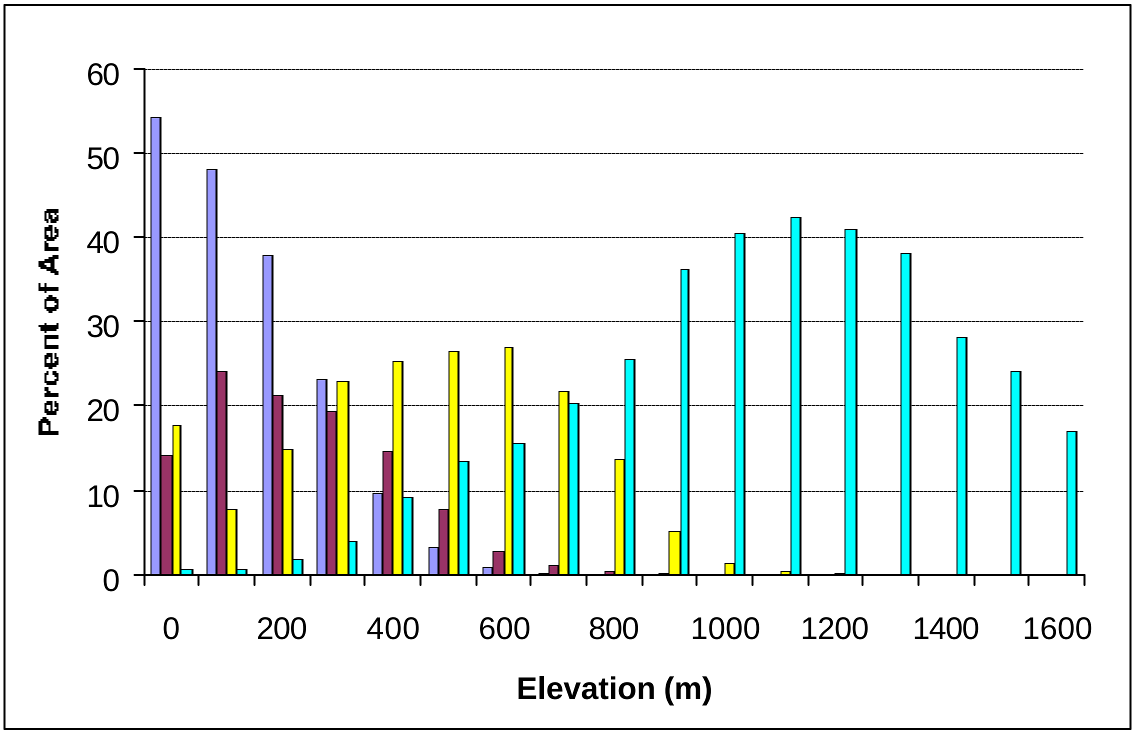
Table 1: Vegetation in Interior Alaska (USGS classification)

Area (km^2)	Vegetation type
83,872	White, black spruce forest
48,463	Black spruce, tamarack, lichen woodland
48,138	Deciduous forest and tall shrubs (willow, birch, alder)
20,049	Spruce woodlands and shrub bogs
17,330	Spruce forest
15,558	Mixed forest (aspen, birch, balsam poplar, black and white spruce)
14,780	Open spruce forest with tall shrubs (willow, birch, alder)
13,773	Woody arctic tundra (dwarf/low shrubs)
11,907	Shrub fens and bogs
5,133	Woody Arctic tundra, tall, low, and dwarf shrubland
3162	Others

All four major vegetation classes prefer flat to gentle slopes of <15% and show a steep decline in abundance with increasing slope (Figure 2.3).

'White, black spruce forest' showed a clear preference for low elevation (<500m), W to NW exposure, and flat slopes. Forty-three percent of the vegetation class could be found between 200m and 300m elevation, 96% was below 500m. Almost half of this classification could be found at W to N aspects with a maximum at a NW aspect. There was a clear preference for gentle slopes (<5%) with 81% of the occurrence.

Figure 2.3: Distribution of vegetation types by elevation and slope



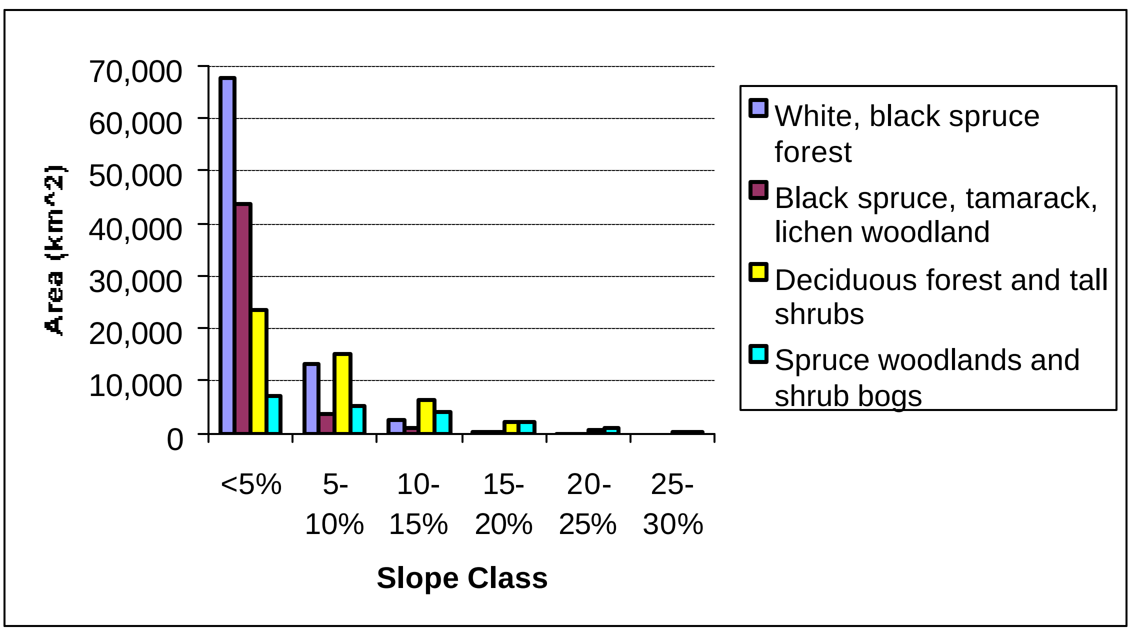
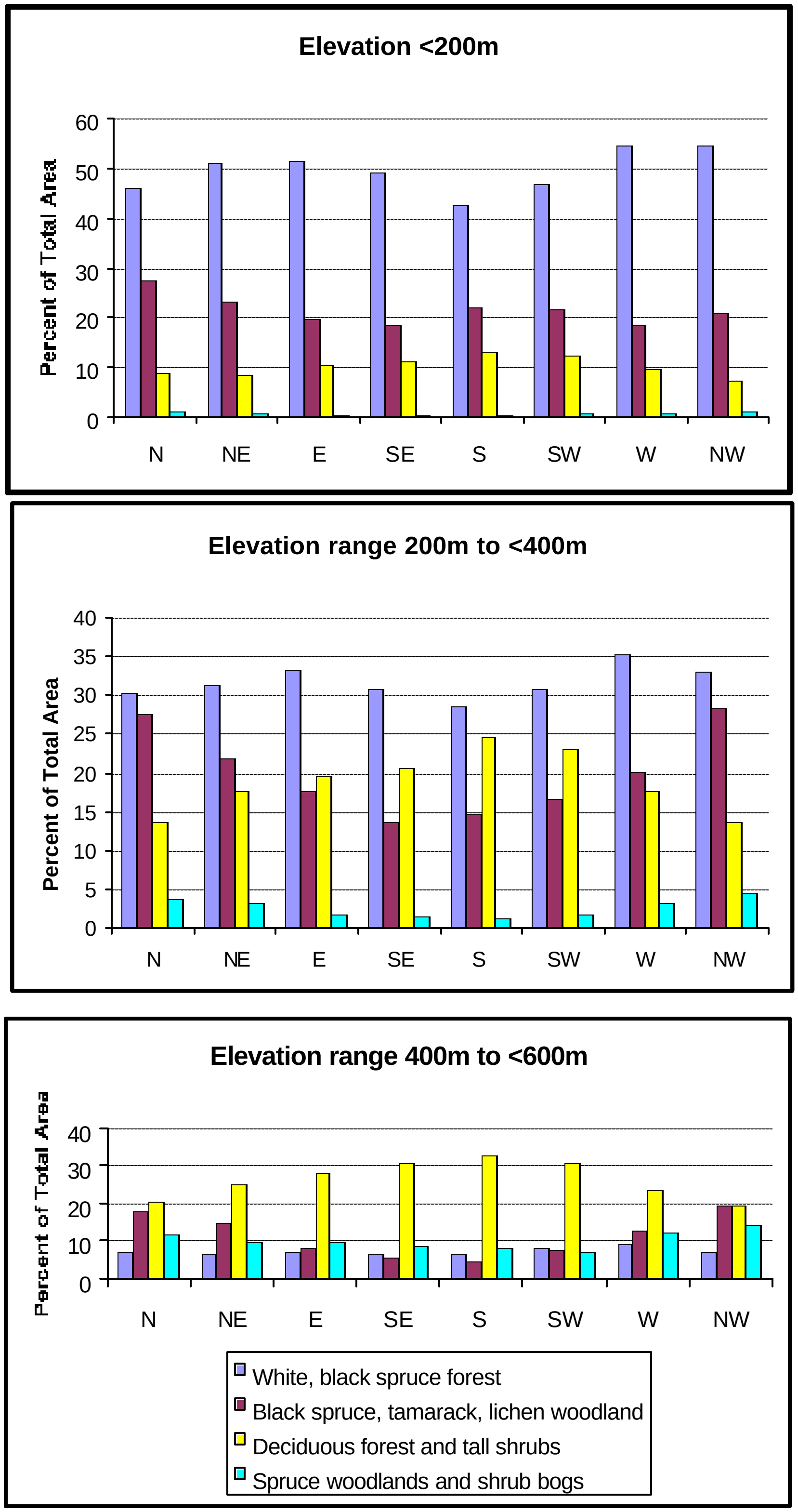


Figure 2.4: Distribution of vegetation types by aspect and elevation



‘Black spruce, tamarack, lichen woodland’ had similar preferences to the ‘White, black spruce forest.’ It also preferred low elevations (100m to 500m), W to NE aspects and gentle slopes. It was most abundant at 100-200m (31% of the vegetation class) with decreasing abundance with increasing elevations (27%, 17%, and 9% at 200-300m, 300-400m, and 400-500m, respectively).

‘Deciduous forest and tall shrubs’ (including willow, birch, alder) could be found at a much wider range of sites than the previous two black spruce classes. It was found at 0-700m elevations with a peak at 300-400m (21% of the vegetation class) and at all aspects with only a slight preference for S and SE aspects (15% each). Only half of this vegetation class occurred at <5% slope, one third was found at 5-10% slope, 13% at 15-20% slope, and another 5% at 20-25% slope.

‘Spruce woodlands and shrub bogs’ covered the most diverse elevation ranges and all aspects with peaks at NW (19% of the vegetation class) and N (17%) and the least occurrence at SW (9%). The preferred elevational range was between 400m and 500m with 13% of the total area. Seventy-six percent of the total observed area covered by this vegetation class was found at 300m to 1000m, and it could still be found at up to 1200m in a few instances. The slope class distribution was similar to the ‘deciduous forest and tall shrubs’ class except ‘spruce woodlands’ was better represented at even steeper slopes. The abundance of this vegetation class with increasing steepness was: 36% at <5% slope, 27% at 5-10% slope, 20% at 10-15% slope, 11% at 15-20% slope, and 5% at >25% slope.

2.4.3 Fire Distribution in Interior Alaska

From 1950 to 1999 a cumulative total of 65,000km^2 burned in all of Alaska, out of which 99% occurred in Interior Alaska. The AFSD (Alaska Fire Scar Database) contains no fires in Interior Alaska for 1960 to 1967 due to lost records. In all other years, total area burned varies from 2km^2 to 8,900km^2. During the 50-year time period in Interior Alaska, 3km^2 (3 pixels) burned 4 times, 280 km^2 burned three times, 4070 km^2 burned two times, and 55,570 km^2 burned once. Average fire return interval between the first two fires was 19±13 (mean ± standard deviation) years. In contrast, fire return interval between fires 2 and 3 was only 10±10 years indicating a potentially decreasing fire return interval; however, this interpretation is based on only a few years of fire information and only a few fires.

2.4.3.1 Fire versus Elevation

With the exception of below 100m elevations, fire occurrence decreases strongly as elevation increases (Figure 2.2). The distribution of fire within the landscape is very similar to the distribution of elevation ranges. The elevation ranges that experience the most burns are in decreasing order: 100-200m (29% of all fires in Interior Alaska, 25% of the land area in Interior Alaska), 200-300m (28% of all fires, 21% of the land area), 300-400m (18% of all fires, 15% of the land area). Thus from 100m to 400m elevations, there is a higher likelihood for fire than at elevations above 400m. Below 100m, the landscape probably consists of floodplains which are less fire-prone. The theoretical fire cycle for the different elevation intervals are 289 years for the floodplain, 196 years for 100-200m elevation, 166 years for 200-300m, and 187 years for 300-400m.

2.4.3.2 Fire versus Aspect

The fires in Interior Alaska from 1950 to 1999 were distributed almost evenly over all aspects with only a slight increase at N and NW aspects (Figure 2.2). However, the aspects are not distributed evenly throughout the landscape. If the landscape is divided into north versus south, 54% has a northern and 46% has a southern aspect. When fire occurrence at each aspect is normalized by the total area of each aspect in the landscape, S, NW, and SW aspects are more fire-prone. Of all the area having a S aspect 24% burned during 50 years compared to 23% at either NW or SW aspects. Clearly, due to the disproportionate distribution of aspects in the landscape, the aspect that experienced the most fires does not have the highest likelihood to burn. Aspect analysis is also sensitive to the number of aspect classes used. When only four aspect classes are used (N, E, S, W), fire occurrences average out and the S aspect is only slightly more fire prone than the other aspects. Of all area having a S aspect, 23% burned, compared to 22% at each of the other aspects (21.6% to 22.3%). Theoretical fire cycles for the different aspects range from 211 years at the S aspect to 236 years at the W aspect.

2.4.3.3 Fire versus Slope

Sixty-five percent of the landscape has a slope of 0-5% and received 78% of all fires (Figure 2.2). Twenty-one percent of the landscape has a slope of 5-6% with 16% of all fires, and 9% of the landscape has a slope angle of 5-10% and experienced 5% of all the fires. Clearly, there is a decrease of fire incidence with increasing slope angles.

2.4.3.4 Combined Topography Classes

When all three topographic classes are combined, one would thus expect the highest fire incidence at 100m to 300m elevation, <5% slope, and S, NW, or SW aspect. However, when elevation range, aspect, and slope were compared to fire simultaneously, the pattern was not that simple. To make the data more manageable, only fire areas of at least 500km^2 at any topographic combination were considered, and aspect was reduced to 8 classes. This yielded at total of 80 topographic combinations. All topographic combinations meeting the conditions of fire size >500km^2 fall between 100m and 400m elevations, all aspects, and less than 5% slope angle. At 0-100m elevation, fires occurred at all aspects and 0-1% slope. At 100-200m, fires occurred at all aspects and slopes varied from 0-3%. At 200-300m, fires occurred at all aspects and slopes from 0-4%. At 300-400m, fires occurred at the N aspect from 0- 4% slope, at E and SE aspects from 0-3% slope, at the W aspect from 2-4%, and at the NW aspect from 0-5% slope. This shows that fires occurred at increasing slope angles with increasing elevation. Also, at elevations above 300m, there is no fire at SW and NE aspects.

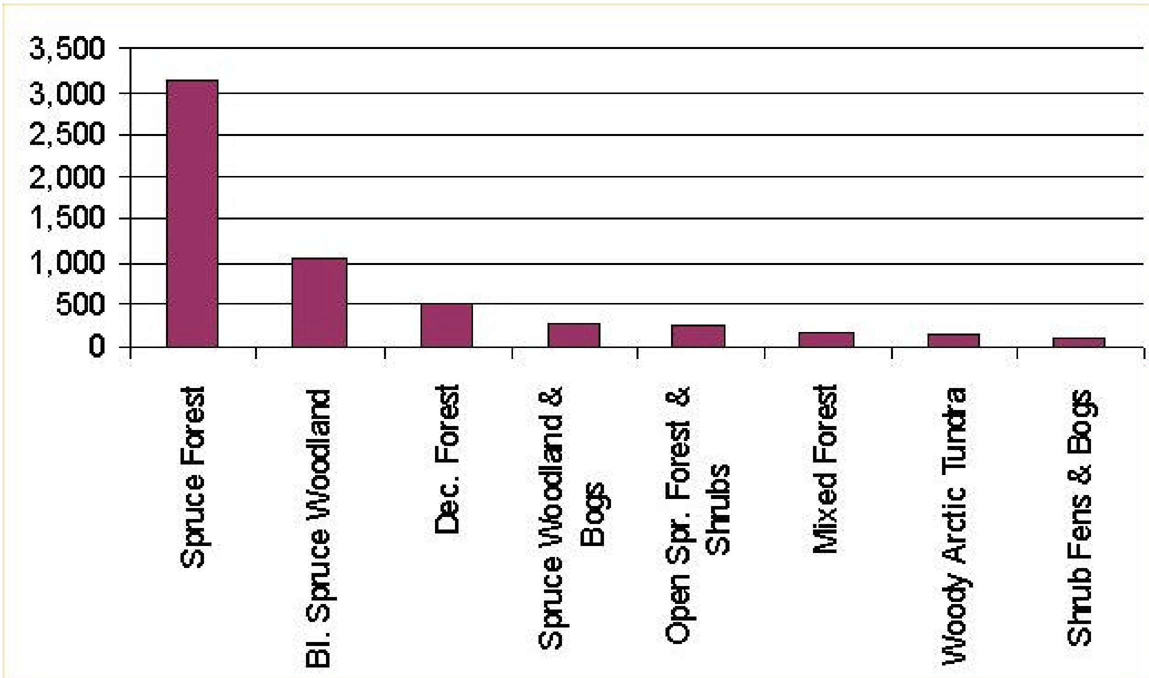
2.4.4 Fire History versus Vegetation Type

The relationship between fire and vegetation was analyzed in two parts: flammability, or 'which vegetation types burned most often?' and succession or 'which vegetation types regrew for how long after each fire?' To reduce noise in the data set, only vegetation types that covered at least 5,000km^2 or 4% of Interior Alaska were included which resulted in 9 vegetation types. Since the vegetation classification was created in 1992/1993, only fires from 1994 to 1999 could be used for the flammability analysis. Succession could only be determined using the time span from the last fire until 1992.

2.4.4.1 Flammability of Vegetation Types

From 1994 to 1999 the total burned area encompassed 6,000km^2. Forty percent of this fell into the 'White, black spruce forest' vegetation type which covers 29% of the area. Seventeen percent of the total area burned was classified as 'Black spruce, tamarack, lichen woodland' (which covers 17% of the area), and 13% was classified as 'Spruce forest' (only 6% of the area). However some of these vegetation types cover a much larger area than others. The largest area burned by vegetation type was 4.4% in 'Spruce forest,' followed by 3% in 'White, black spruce forest' and 2% each in 'Black spruce, tamarack, lichen woodland' and 'Open spruce forest with tall shrubs' (Figure 2.5)

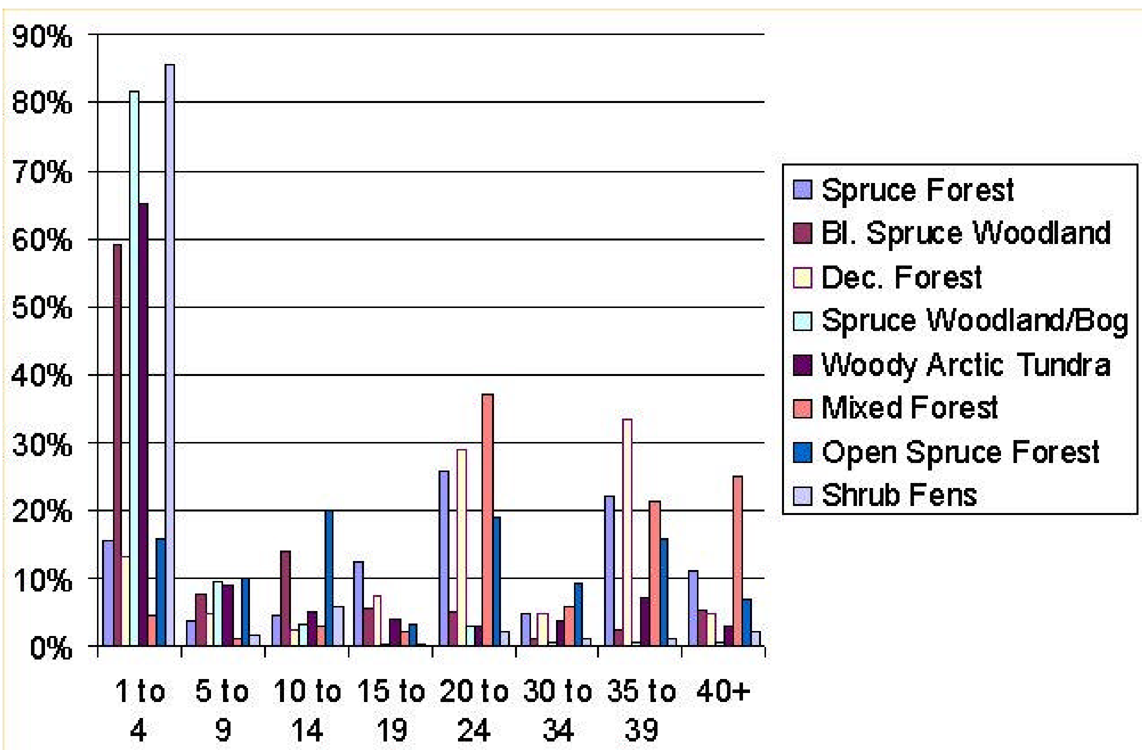
Figure 2.5: Flammability: total area burned (in km^2) from 1994 to 1999 by vegetation type



2.4.4.2 Succession after Fire

To determine succession since fire, fires from 1950 to 1991 were compared to the vegetation classification performed in 1992/1993. Data were organized by years since last fire and grouped into 5-year intervals (Figure 2.6). The area burned in each time interval was strongly dominated by the two major vegetation types 'White, black spruce forest' and 'Black spruce, tamarack, lichen woodland.' When the data were normalized by area covered by each vegetation type, four vegetation types showed a strong response to years since fire. Of all the area classified as 'Shrub fens and bogs,' 86% were found 1 to 4 years after the latest fire. Other vegetation classes in this time interval were 'Spruce woodlands and shrub bogs' (82% of all the pixels classified as this vegetation type), 'Woody arctic tundra' (60%), and 'Black Spruce, Tamarack, Lichen Woodland' (60%). 'White and Black Spruce Forest' and 'Deciduous forest and tall shrubs' mostly fell into the 20-24 years and 35-40 years since fire categories. Thirty-seven percent of the area classified as 'Mixed Forest' had burned 20 to 24 years before, 47% had burned 35 to 42 years before. Since there was very little fire information for the 1960s, no vegetation succession can be determined for the period from ca. 25 to 35 years after the fire.

Figure 2.6: Succession: distribution of vegetation types (in percent) by years since last fire



2.5 Discussion

This study confirms that the stand-level links among fire, topography (elevation, aspect, slope), and vegetation in Interior Alaska are still detectable at 1km resolution. Topography not only influences the distribution of vegetation types, but also (indirectly) the distribution of fires because some vegetation types are more likely to burn than others.

This analysis determined that at a regional scale, the vegetation in Interior Alaska ranges from spruce forest at low elevations to deciduous forest at intermediate elevations to shrubs and bogs above approximately 800m. One exception is floodplains at low elevations, which are dominated by the 'Deciduous forest and tall shrubs' type. In general, the forested vegetation types cannot grow on steep slopes and black spruce types are more likely to dominate on cold northerly aspects.

Spruce stands (especially black spruce) provide large amounts of fuel for fires with their usually thick lichen, moss or organic layers interspersed with dead and low branches (Viereck and Schandelmeier 1980, Johnson 1992). Deciduous stands, in contrast, have higher foliage moisture content and less fine fuels such as needles, twigs, resinous products, and bark flakes. Thus, fire can spread much more rapidly through a coniferous forest and jump up into the crowns (Johnson 1992). This analysis shows that on a regional scale, spruce forest types are more fire prone than deciduous forest types. What also becomes apparent is that most fires occur at low elevations and low slope angles. As these topographic areas are predominantly covered by spruce forest, it is not clear if topography or vegetation type is promoting large-scale fires. Aspects with the highest amount of sunlight (SW, S, NW) are most susceptible to fire which could be attributed to either the fact that they are drier and warmer or that they are less likely to contain spruce forest.

Bergeron (1991) found that the fire regime for the past 300 years in northwest Quebec was controlled by both regional and local factors. At the local scale (on islands), abiotic factors such as topography and potentially higher occurrence of lightning strikes resulted in more frequent but smaller fires. At the regional scale, fires were less frequent, more intense, and larger, thereby reducing the effect of topography. Campbell and Campbell (2000) attributed a decline in fire activity at the southern boreal forest boundary in Alberta to species composition. The more fire-prone shrub birch (*Betula glandulosa*) had been replaced by aspen (*Populus tremuloides*) due to hydrological changes in the landscape. In northern Alberta, fire frequency increased with distance from water breaks (Larsen 1997). There is clearly a direct connection between topography and fire as ridges can function as fire breaks or wind can carry fire from ridge to ridge while the fire is physically unable to burn downhill (Bergeron 1991, Rupp *et al.* 2000). Accordingly, in the sub-alpine forest of Wyoming, fire was more frequently observed on ridge tops than in protected valley bottoms and ravines (Romme and Knight 1981).

My analysis for Interior Alaska indicates that a large majority of the fires since 1993 took place in some type of spruce forest or spruce woodland and that spruce forest types are most likely to burn. Therefore in Interior Alaska at the regional scale, fires are mostly promoted by vegetation type regardless of topography. However, topography is a critical factor in the distribution of vegetation types on the landscape and therefore indirectly responsible for fire behavior.

Since white and black spruce differ in their ecological characteristics, their location on the landscape and their relationship with fire, it would have been very important to have them in separate classes in the regional vegetation classification. Unfortunately, this was not the case because white and black spruce are indistinguishable by spectral signature. Another problem is the shortness of the historic fire record of only 50 years which is less than any fire cycle. Since the USGS vegetation classification is based on satellite data for 1992-1993, this produces only forty years (1950 to 1992) of both fire and vegetation information to determine succession trajectories after fire disturbance. This time period is not long enough for solid conclusions from the record. Likewise, there are only ten years of data to determine the flammability of vegetation types.

The causal relationships among fire, topography, and vegetation are important inputs into regional boreal forest models. Models have to realistically reproduce naturally occurring relationships before we can simulate potential future changes in the boreal forest due to climate change. Despite the coarseness, 1km resolution data seem adequate for regional boreal forest modeling. Most importantly, there is an urgent need for a better land cover classification that clearly separates among the major ecological types black spruce, white spruce, and deciduous forest.

2.6 Conclusions

Despite the coarseness of the classification at 1km^2 scale, patterns regarding vegetation and topography reflected those described in field studies at the local scale. The four major vegetation classes arrange themselves along gradients of elevation and to some degree aspect. Steep slopes cannot support forests. Fire incidence peaks at 100-200m, S, NW, and SW aspects, and decreases with rise in either elevation or slope. Vegetation classes containing black spruce are more flammable than other types. On a regional scale it seems that topography dictates vegetation type distribution which in turn influences fire behavior. Vegetation succession after fire disturbance was not clear due to the coarseness of the vegetation classification and the lack of a long-term record of post-fire vegetation.

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Chapter 3 – A hierarchical logistic regression model for vegetation type prediction

3.1 Abstract

In order to understand drivers of vegetation type distribution and change in Interior Alaska, a logistic regression model was developed. This model predicts the four major vegetation types: tundra, deciduous forest, black spruce forest, and white spruce forest based on elevation, aspect, slope, drainage type, fire interval, average growing season temperature, and total growing season precipitation. The model was run in three steps. At the first step tundra was distinguished from forest, which was mostly driven by elevation, precipitation, and south to north aspect. At the second step forest was separated into deciduous versus spruce, which was mostly driven by fire interval and elevation. At the third step, the identification of black versus white spruce was driven mainly by fire interval and elevation. The model was validated in Interior Alaska and Northwest Canada where it could predict vegetation with overall accuracy of 68% to 93%. The logistic regression model could also be used to distinguish bog vegetation from all other vegetation types and improved in predictive ability when actual fire history was included as a predictor.

3.2 Introduction

Boreal forests form a circumpolar belt spanning over 20° latitude covering North America and northern Eurasia, and containing one of the largest carbon reserves in the world in their water-logged soils (Post *et al.* 1982, Barbour *et al.* 1987, Apps *et al.* 1993, Ping *et al.* 1997). Boreal and arctic Alaska has been experiencing warmer temperatures and increased precipitation in recent years which has led to changes in sea ice, glaciers, permafrost, and vegetation (Myneni *et al.* 1997, Serreze *et al.* 2000, Keyser *et al.* 2000, Jorgensen *et al.* 2001). Overall, the responses of ecosystems to climate change are complex and varied at various time and spatial scales (Shaver *et al.* 2000). Changes in ambient temperatures and precipitation patterns are expected to also affect fire frequency. There are indications that fire frequency has been increasing in Western Canada (Stocks *et al.* 1998, Harden *et al.* 2000, Chapin *et al.* 2000) while decreasing in Eastern Canada (Bergeron and Archambault 1993, Flannigan *et al.* 1998, Carcaillet *et al.* 2001). Another concern is that changes in temperature, moisture, and permafrost could lead to a release of carbon stored in boreal bogs (Yu *et al.* 2001, Turetsky *et al.* 2002). Considering the vast amounts of carbon stored in the boreal forest, consequences of future climate change at high latitudes will significantly alter the global carbon budget with potentially important feedbacks between the boreal forest and global climate (Foley *et al.* 1994, Eugster *et al.* 2000, Chapin *et al.* 2000).

The majority of the Alaskan boreal forest is located in the Interior of the state. This region is characterized by five major plant community types: black spruce, white spruce, deciduous forest, and bog (Viereck *et al.* 1983, Van Cleve *et al.* 1983, Yarie and

Van Cleve 1983, Viereck *et al.* 1986, Szeicz and MacDonald 1995, Van Cleve *et al.* 1996). Black spruce (*Picea mariana*) and moss forests dominate on cold and poorly drained sites located on north-facing slopes, lowlands, and lower slopes. Black spruce is the most widespread forest type and is usually located on permafrost. After a severe fire, deciduous regrowth is replaced by a dense black spruce/moss forest after approximately 50 years and mature black spruce forest after 100 years. White spruce (*Picea glauca*) is found on warm and dry south-facing upland sites and at treeline. On upland white spruce sites the successional sequence is very similar to black spruce sites except there is more hardwood present. When a stand-replacing fire occurs, a dense hardwood stage can be found after 25 years, a mature hardwood stage after 50 years, a mixed white spruce-hardwood stage after 100 years, and the mature white spruce/moss stage after 200 years. Dry sites often support deciduous forest containing paper birch (*Betula papyrifera)*, quaking aspen (*Populus tremuloides)*, and balsam poplar (*Populus balsamifera*), while very wet sites can sustain tamarack (*Larix laricina*). In the absence of fire, a boreal forest stand becomes increasingly cold and wet and can potentially turn into a bog (Glebov and Korzukhin 1992). There are indications that climate change is leading to a degradation of permafrost in Interior Alaska thereby destroying the current forest and increasing the number and size of bogs (Jorgensen *et al.* 2001).

Black spruce is more prone to fire than white spruce or deciduous stands with an average fire cycle from 80-90 years in the MacKenzie Valley in Canada (Rowe *et al.* 1974) to 100 years in closed spruce in Alaska (Heinselman 1981). Open spruce-lichen forests have mean fire cycles of 130 years (Heinselman 1981) compared to 300 years for alluvial white spruce sites (Rowe *et al.* 1974).

As the vastness and inaccessibility of the boreal forest of Interior Alaska seriously impedes extensive field studies, modeling offers an alternative to understanding more about the processes of this region. Currently, there are only very few models available for Interior Alaska. Rupp *et al.* (2000a, 2000b) developed a model for vegetation change in Alaska called ALFRESCO. This model simulates four vegetation types: upland tundra, broad-leaved deciduous forest, white spruce forest, and dry grassland and their transient responses to changes in climate, disturbance regime, and seedling recruitment. The model was originally developed as a point model (Rupp *et al.* 2000a) and extended to be more spatially explicit (Rupp *et al.* 2000b, Rupp *et al.* 2001). Another model for Interior Alaska is the Spatial Alaskan Forest Ecosystem Dynamics (SAFED) model which is a geographic model that uses major limiting factors to drive processes in three primary components: above and below ground forest growth, litter fall, and decomposition (Yarie 2000a). The model is based on nitrogen productivity for forest growth, litter fall quantity and quality, and microbial efficiency for decomposition. SAFED is driven by climate, topography, and disturbance where climate and ecosystem-level disturbances are simulated as stochastic processes. The model was developed in a GIS and has been verified on an individual tree basis in a floodplain old growth white spruce forest in interior Alaska, but it is designed to work at various spatial scales. So far SAFED has been validated in four vegetation types in interior Alaska: an alder-balsam poplar site, an old growth balsam poplar and white spruce site, a mixed deciduous and aspen site, and a white spruce site (Yarie 2000b).

Simpler types of models are equilibrium simulations of potential vegetation such as the Holdrige life zone model (Holdridge 1967). One mathematical tool for prediction modeling is logistic regression, which determines the probability of occurrence of a bivariate response variable such as yes/no, presence/absence, type A/type B (Hosmer and Lemeshow 2000). It can be widely applied to a variety of fields and has for example been used for risk assessment (Jalkanen and Mattila 2000), habitat evaluations (Pearce and Ferrier 2000), and the prediction of vegetation distribution (Hilbert and Ostendorf 2001). Logistic regression requires explanatory variables or predictors, which are used in the model to predict the response. The basic equation for logistic regression can be broken down into two parts. The first is the linear equation where

$$\text{Response } Y = \text{intercept} + a_1 * \text{variable1} + a_2 * \text{variable2} + \ldots + a_n * \text{variable } n$$

where the response Y is the expected value of y given the constants a_i and any number of predictor variables.

The second part is a transformation of the linear equation using a dichotomous logistic distribution. Now the probability of the response can be mathematically expressed as

$$P(x) = \frac{e^{(\text{intercept} + a1 * var1 + a2 * var2 \ldots + an * varn)}}{1 + e^{(\text{intercept} + a1 * var1 + a2 * var2 \ldots + an * varn)}}$$

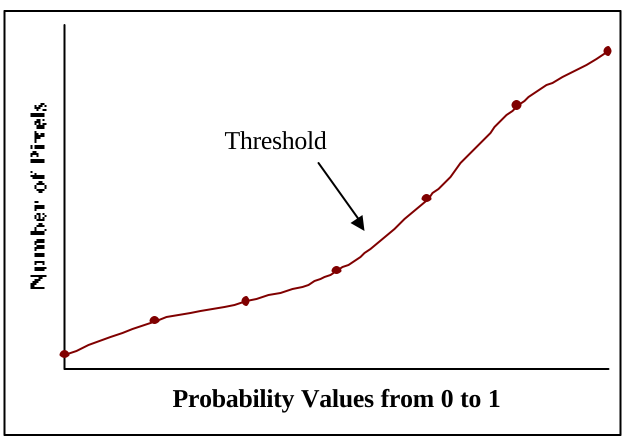
This equation provides a probability value from 0 to 1.0. Depending on a chosen threshold value, everything above this threshold equals one state of the bivariate response, while everything below equals the other state of the variable (Figure 3.1). Depending on how this threshold value is increased or decreased, there will be more or less of either bivariate state in the outcome. By comparing estimated outcomes with known states, the value for the threshold with the highest prediction accuracy can be determined. Accuracy can be tested by running predictions over a range of threshold values and composing an accuracy table (e.g. Table 3.1). Total accuracy can then be calculated as

Accuracy = (total true) / (total predicted) (Pearce and Ferrier 2000).

Table 3.1: Logistic regression accuracy table

	Actual 0	**Actual 1**
Predicted 0	True	False
Predicted 1	False	True

Figure 3.1: Determining the best threshold value for logistic regression



The purpose of this study is the development and testing of a logistic regression model that predicts major vegetation types in Interior Alaska. Logistic regression results can be statistically evaluated to identify the importance of model parameters and drivers of vegetation type predictions. The resulting equilibrium model can then be used to evaluate the response of four major vegetation types of Interior Alaska (black spruce forest, white spruce forest, deciduous forest, and tundra) to climate change by changing predictor values.

3.3 Methods

The logistic regression model was developed for Interior Alaska (Figure 3.2) using the following inputs as parameters: elevation, aspect, slope, drainage, mean growing season temperature, total growing season precipitation, and fire return interval. Information on years since last fire was not included in the originally model, because I wanted to see how accurate the model would be without it. Instead, the effect of including actual fire history was evaluated in a separate modeling exercise. The total study area encompasses almost 300,000km^2. While the logistic regression statistics were performed in SPLUS (MathSoft, Inc., Seattle, WA) all data overlays and manipulations were done in a Geographic Information System (Arc/Info 8.02 by Environmental Systems Research Institute, Inc., Redlands, CA).

3.3.1 Datasets

Vegetation: Within the scope of a different modeling project titled the Western Arctic Linkage Experiment (WALE) at the University of Alaska Fairbanks (http://picea.sel.uaf.edu/projects/wale.html), several investigators created a land cover classification for the Western Arctic (Alaska and adjoining Western Canada) with the following nine land cover classes: ice, rock/lichen, prostrate shrub (tundra), dwarf shrub (tundra), low shrub, deciduous forest, black spruce forest, white spruce forest, coastal forest, and lakes a (Rupp, Silapaswan, Copass unpublished data). Since none of the currently available 1km resolution land cover classifications for Alaska distinguish between the two ecologically most important vegetation types, black and white spruce forests, Rupp (unpublished data) developed an algorithm that refines Fleming's (1997) land cover classification for Alaska. Rupp's algorithm is based on growing season temperature, latitude, elevation, and slope, following Viereck and Van Cleve's generally accepted theories on vegetation type distributions in the Alaskan landscape (Van Cleve *et al.* 1986, Viereck *et al.* 1992): black spruce forest is predominantly located on flat slopes at low elevations and at northern aspects, while white spruce forest dominates active floodplains and the timberline (Rupp, personal communication). Vegetation data for Canada was originally a 1995 AVHRR (Advanced Very High Resolution Radiometer) based map containing 31 different land cover types across Canada, produced jointly by the Canadian Centre for Remote Sensing and the Canadian Forest Service (Cihlar *et al.* 1996, Cihlar and Beaubien 1998). Copass and Silapaswan (unpublished data) applied a version of Rupp's algorithm to this Canadian dataset to produce the same major vegetation types as for the Alaska map. Unfortunately, they were not able to separate white spruce from black spruce in Canada, as the distribution of these vegetation types is not the same across the border. While white spruce constitutes the timberline in Alaska, black spruce takes its place for no apparent ecological reason in Canada. Finally, they adjusted Rupp's Alaskan vegetation to produce a continuous vegetation map for the Western Arctic. To further reduce vegetation classes for the logistic regression model for

Interior Alaska, I combined prostrate shrub (tundra), dwarf shrub (tundra), and low shrub as 'tundra.' Interior Alaska contains no pixels classified as water, coastal forest, or rock/lichen. The resulting vegetation classification was used in development, verification and validation of the logistic regression model while unvegetated area (ice) was ignored.

The WALE classification does not contain a separate bog vegetation class. High-latitude climate change is expected to affect this vegetation type in particular due to changes in soil moisture regime and permafrost (Jorgensen *et al.* 2001). I therefore felt it was important to see if bog vegetation could be distinguished from any other vegetation type using the logistic regression model. The location of bogs was imported from the AVHRR based 1km resolution North American Land Cover Characteristics Database (Loveland *et al.* 1999) analyzed in the previous chapter. This vegetation data set contains 38 land cover types for Interior Alaska out of which four account for 70% of the Interior Alaska land area. The ninth most abundant vegetation type from this classification is 'shrub fens and bogs' covering 4% of Interior Alaska. Pixels with this vegetation type were incorporated into the WALE vegetation map. This resulted in a total of six land cover types in Interior Alaska: ice (covering 0.1% of Interior Alaska), tundra (24%), deciduous forest (23%), black spruce (39%), white spruce (10%), and bog (4%) (Figure 3.3).

Figure 3.2: Boundary for Interior Alaska used for this study

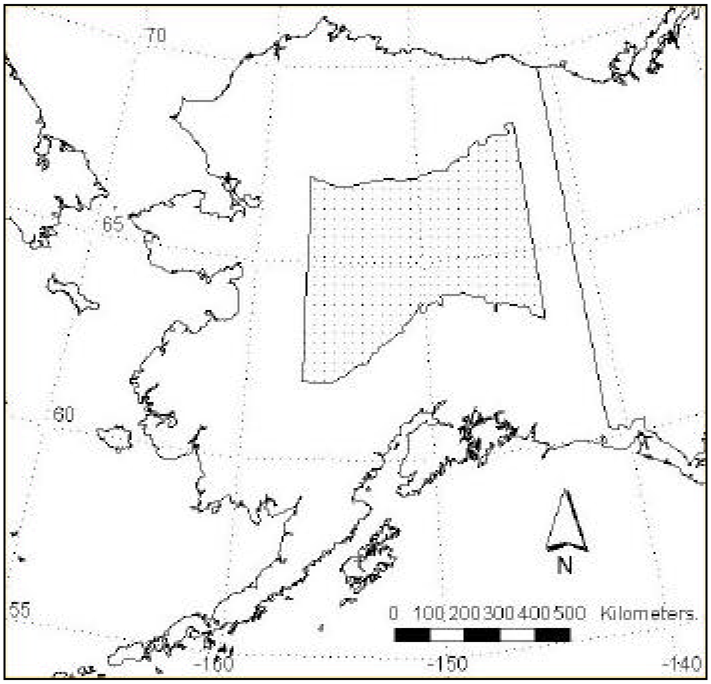
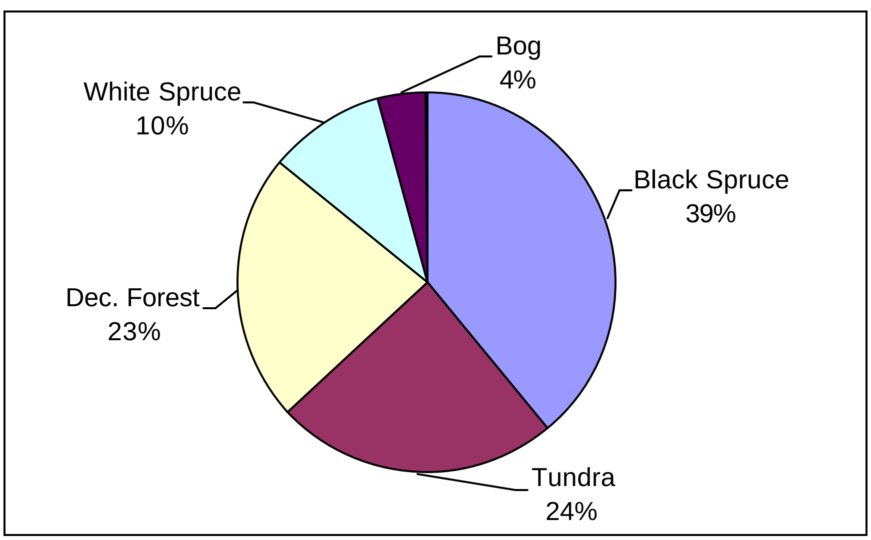


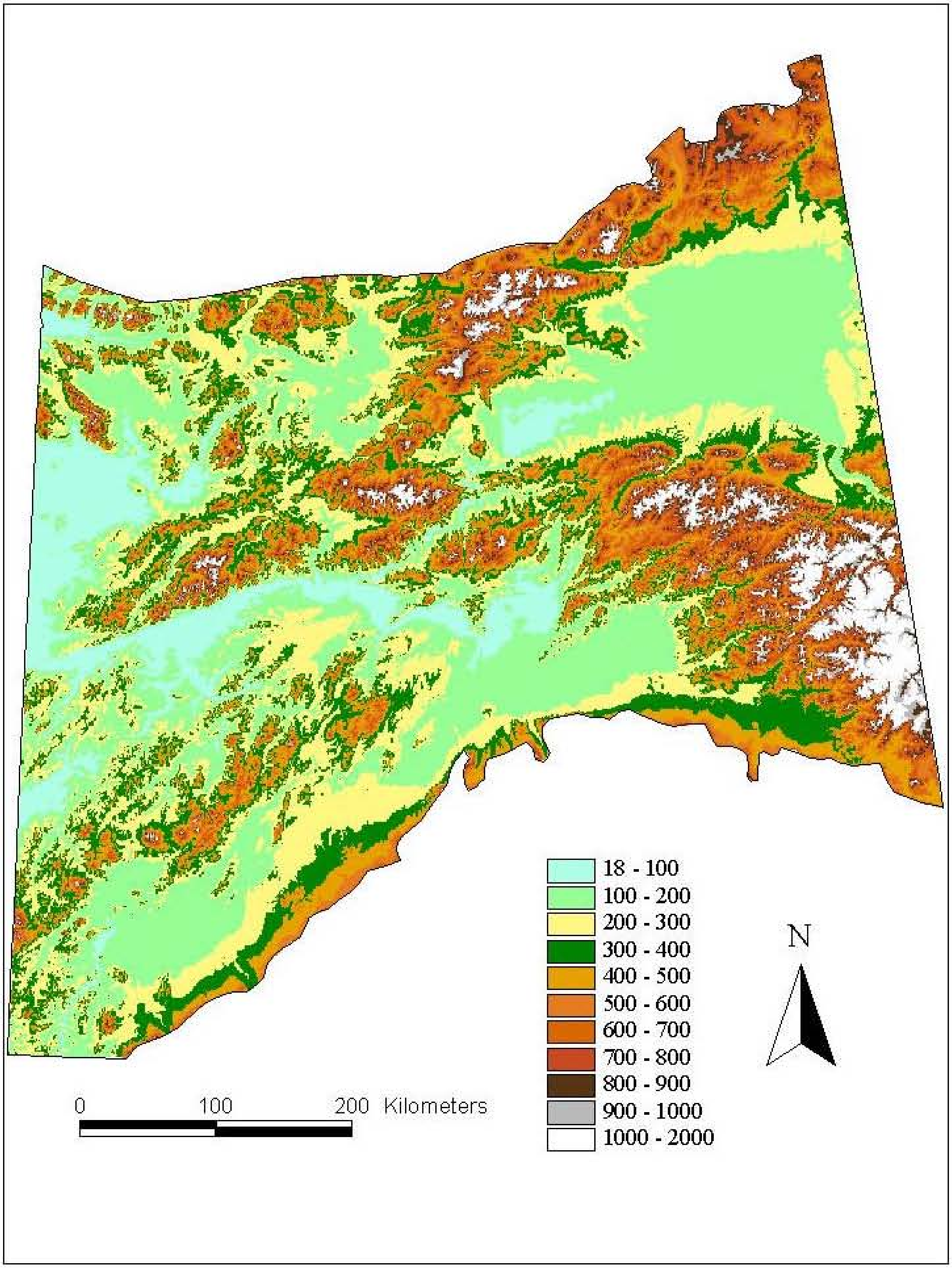
Figure 3.3: Vegetation distribution in Interior Alaska



Topography: A 1km resolution USGS global digital elevation model (DEM) was used to calculate elevation, slope (in percent) and aspect (in degree) (Figure 3.4). When aspect is treated as a continuous variable from 0 to 360 degrees it produces erroneous results because the two values at opposite ends of the gradient are actually the same in the landscape (i.e. northern aspect). Aspect values were therefore processed into two variables: southern versus northern aspect, and eastern versus western aspect. In the first case, values increase from 0 at southern aspect to 180 at northern aspect with a value of 90 at western and eastern aspects. In the second case, eastern aspects were assigned zero and western aspects were assigned 180 with 90 at south and north aspects. When aspect is broken down into eight discrete aspect classes or flat (no aspect), seventeen percent of Interior Alaska shows no particular aspect (flat). The most common aspect is southern (13% of Interior Alaska) the least common is northern (6%). Elevation ranges in Interior Alaska from 18m to 1830m. Sixty percent of Interior Alaska is located at elevations between 100m and 400m. Slopes range from 0% to 38%. Only 5% of Interior Alaska has slopes of zero to 1% angles. Fifty-five percent of the landscape has slopes of 1% to 5%.

Soil drainage classes were imported from the USDA STATSGO (State Soil Geographic) database (http://www.il.nrcs.usda.gov/soils/statsgo_inf.html). Drainage class reflects the speed at which water is removed from the soil after a rainfall event. Drainage values range from one to seven where one stands for 'excessive' (meaning very rapid water loss after a rain event) and seven stands for 'very poor' drainage leading to waterlogged soils. Forty-six percent of Interior Alaska is classified as 'moderately well' drained. Thirty percent is imperfectly drained leaving the soil wet for a significant part of

Figure 3.4: Elevations in Interior Alaska (in meters)



the growing season, while 16% is poorly drained where the soil remains wet for a comparatively large part of the time when the soil is not frozen.

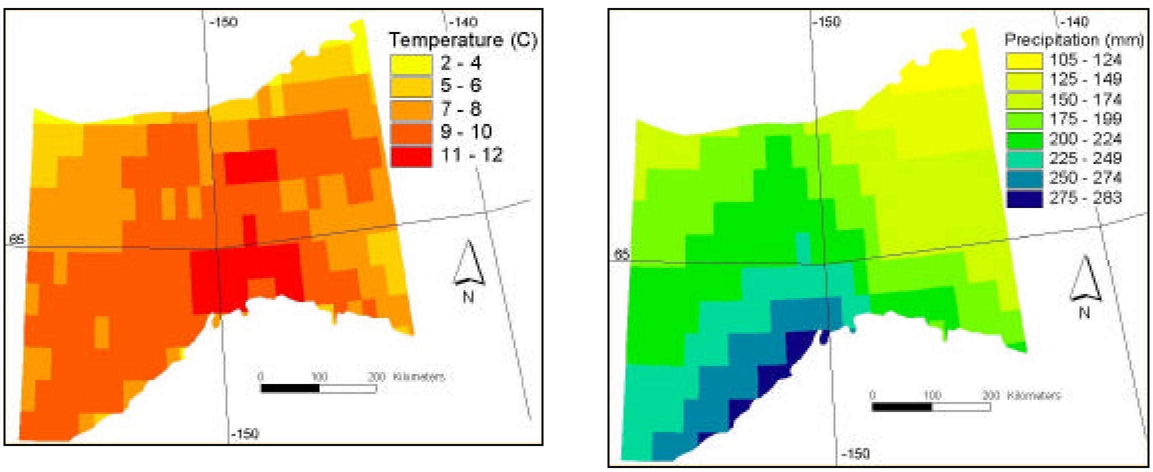
Fire information such as years since the last fire were derived from the historic fire data set for Alaska developed by Kasischke and the Alaska Fire Service (Murphy *et al.* 2000). This data set contains polygon outlines for every fire greater than 1,000 acres in Alaska from 1950 to 1987 and fires greater than 100 acres from 1988 to 1999. This record contains no fires for 1961, 1964, and 1966 because the records were lost.

Fire return intervals are based on the historic fire data set for Alaska. Matt Macander (unpublished data) applied a 150km smoothing kernel (mean) to the actual fire data before summarizing the result by half degree. For each half degree cell, the proportion of annual are burned was calculated as: (area burned 1950 to 2000) / (area of cell * 50 years). The fire return interval was then calculated as the reciprocal (Macander, personal communication). Estimated fire interval in Interior Alaska ranges from 91 to 2000 (representing no fire) years. A fire return interval of up to 200 years is found in 41% of Interior Alaska, and 29% of the area is classified as having a 200 to 300 year fire return interval.

Climate: Temperature and precipitation information for Interior Alaska were extracted from the CRU (Climatic Research Unit) 0.5 degree mean monthly climatology from 1961-1990 (New *et al.* 1999). Growing season temperature was calculated as the average temperature from the five monthly temperatures for May through September. Precipitation was computed as the sum of precipitation over the growing season from May through September. Growing season temperatures vary from 2°C to 12°C with an average of 8.5°C (Figure 3.5). Temperatures are lowest in the northern part of Interior

Alaska and increase towards the south and south-central parts of the region. Total growing season precipitation ranges from 105mm to 283mm (Figure 3.5). Roughly sixty percent of Interior Alaska experiences a total growing season precipitation of 150mm to 220mm. Precipitation is highest along the southwest border of Interior Alaska and decreases along gradients towards the northwest and northeast (Figure 3.5).

Figure 3.5: Average growing season temperature and total growing season precipitation in Interior Alaska (CRU data set)



3.3.2 Model Development

The model uses stepwise logistic regression to identify five major vegetation types: tundra, deciduous forest, black spruce forest, white spruce forest, and bog (including fen).

Since logistic regression can only compare two outcomes at a time, the model was run in three different steps to predict the major vegetation types (excluding bogs):

1.+ Tundra or

+ Forest - > 2. + Deciduous forest or

+ Spruce forest - > 3. + Black spruce forest or

+ White spruce forest

To determine if the logistic regression model could be used to identify bogs in the landscape, bogs were separated from each vegetation type in five additional model runs:

4.+ Tundra or

+ Bog - > 5. + Deciduous forest or

+ Bog

6. + Spruce forest or

+ Bog

- > 7. + Black spruce forest or

+ Bog

- > 8. + White spruce forest or

+ Bog

3.4 Results

3.4.1 Model Verification

To test model accuracy, predictions were compared with vegetation from the WALE classification for each 1km x 1km pixel over a range of threshold values (Table 3.2). Using the best threshold values, the model produces a landscape with less deciduous forest but more black spruce forest than the WALE classification (Figure 3.6, Table 3.2). T-values are generally used as indicators for the importance of predictors for the fitted model (Table 3.3). They are calculated as the regression coefficient divided by the standard deviation of the coefficient and are considered significant above 2.96. High absolute t-values indicate strong predictive powers. Positive t-values indicate a positive effect, while negative t-values indicate a negative effect. According to the model t-values, low temperatures, high elevation, and high precipitation are all strong predictors for the occurrence of tundra vegetation. Deciduous forest responds negatively to an increase in fire interval but positively to increases in elevation. Black spruce is found at gentle slopes and northern aspects, which is how it was defined by Rupp's algorithm. When comparing tundra with bogs, tundra displays a positive correlation with precipitation and fire interval, but a negative correlation with temperature. Bogs could be distinguished from all vegetation types with high accuracy. The highest accuracy for determining bogs (93%) was reached by differentiation of spruce forest (combined black and white) from bog. Bogs were differentiated from all other forest types by high elevations and cold temperatures.

Figure 3.6: Simulated versus actual vegetation

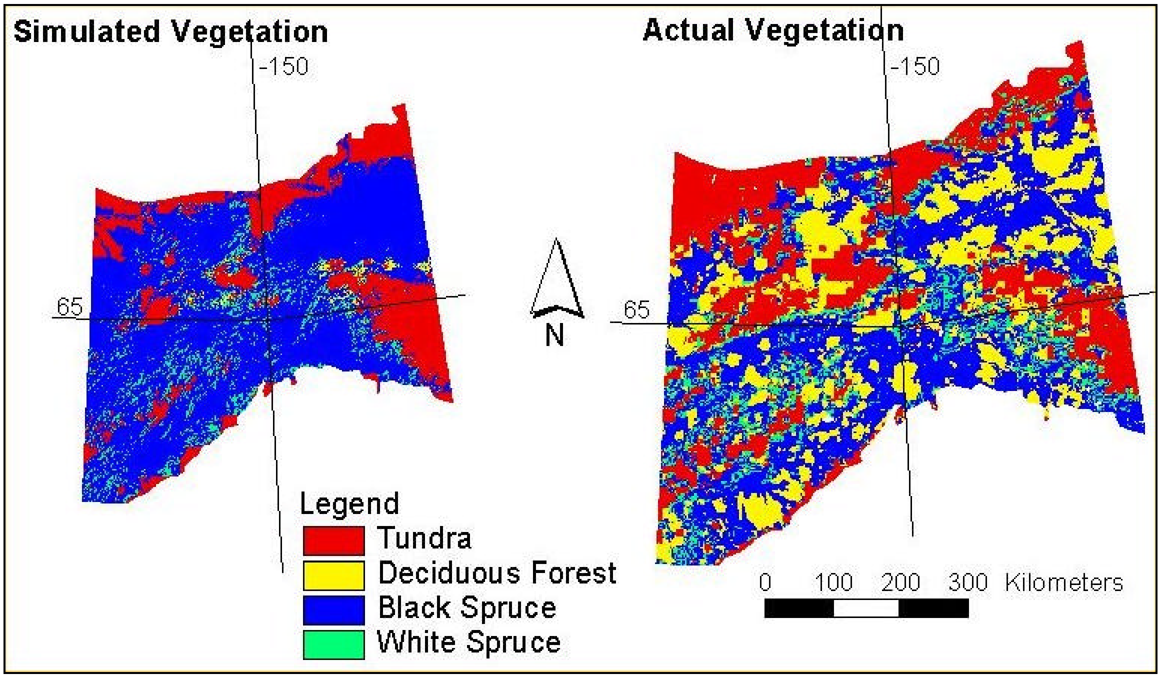


Table 3.2: Simulated versus actual vegetation

Vegetation Type	Simulated	Actual
Tundra	23%	27%
Deciduous Forest	1%	24%
Black Spruce	68%	39%
White Spruce	9%	10%

Table 3.3: Model verification in Interior Alaska*

Simulations	Accuracy (%)	Thresh-old	Most important predictors (t-value)
Tundra vs. Forest	83	0.4	Temperature (-156), elevation (91), precipitation (76)
Dec. Forest vs. Spruce	68	0.5	Fire interval (-69), elevation (51), slope (-27)
Black vs. White Spruce	80	0.5	Slope (-75), S-N aspect (70), precipitation (-47)
Tundra vs. Bog	85	0.6	Precipitation (36), temperature (-32), S-N aspect (-14), fire interval (13)
Dec. Forest vs. Bog	89	0.8	Temperature (55), elevation (-48), fire interval (-24)
Spruce vs. Bog	93	0.4	Elevation (-72), temperature (47), drainage (13)
Black Spruce vs. Bog	92	0.4	Elevation (-69), temperature (46), slope (-18)
White Spruce vs. Bog	79	0.6	Elevation (-47), temperature (37), S-N aspect (-29), fire interval (26)

* Values above the threshold were assigned to the first vegetation type (for example tundra in the first row), while values below the threshold were assigned to the second vegetation type. T-value signs correspond to the first vegetation type listed.

3.4.2 Statistical Model Evaluation

A more accurate statistic model assessment rather than the t-value is the commonly used p-value (if p is zero then it is not possible to reach the same outcome by chance, and the value is significant in predicting the outcome of the regression). I used a p-value of 0.05 as the threshold for significance in the identification of predictors. The resulting p-values reflect the t-statistics very closely (Table 3.4).

Since the model parameters differ in their ranges (e.g. elevation ranges from 18m to 1830m while drainage ranges from 1 to 7), t-values cannot always be directly equated with importance. The differences in range among the input parameters can be removed by standardizing each of the input values using their means and standard deviations in the formula

$$X_{standardized} = (X_i - X_{mean}) / (\text{Standard Deviation } (X))$$

where X_i = ith value for predictor X and X_{mean} = mean value for predictor X.

Since now all input data are reformatted to a scale from -1 to +1, the coefficient values calculated during the regression can be compared with each other directly and their importances can be ranked. T-values remain the same since the ratio of coefficient value to standard deviation is preserved.

Using the standardized regression coefficients instead of t-values produces a slightly different but more accurate ranking of the importance of predictors. According to the standardized values, tundra versus forest is very strongly driven by elevation followed by precipitation (Table 3.5a). This strongly suggests alpine tundra rather than latitudinal tundra in Interior Alaska. Temperature is no longer an important predictor here, but S to

Table 3.4: P values for model parameters

(bold parameters are =0.05 and not significant)

Simulations	Elev.	S-N Aspect	E-W Aspect	Slope	Drain.	Temp.	Precip.	Fire interval
Tundra vs. Forest	<0.01	<0.01	**0.57**	<0.01	<0.01	<0.01	<0.01	**0.96**
Dec. For. vs. Spruce	<0.01	**0.17**	<0.01	<0.01	<0.01	**0.19**	<0.01	<0.01
Black vs. White Spr.	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Tundra vs. Bog	<0.01	<0.01	<0.01	**0.77**	<0.01	<0.01	<0.01	<0.01
Dec. For. vs. Bog	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Spruce vs. Bog	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	**0.05**	<0.01
Black Spr. vs. Bog	<0.01	<0.01	**0.93**	<0.01	<0.01	<0.01	<0.01	<0.01
White Spr. vs. Bog	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01

N aspect (part of Rupp's algorithm) and fire interval are important. For deciduous forest versus spruce forest the t-values and standardized values agree on the two most important predictors: fire interval and elevation (Table 3.5b). According to the standardized values, black versus white spruce is driven by fire interval, elevation, and S-N aspect, as compared to slope, S-N aspect, and precipitation according to the t-values (Table 3.5c). The main driver for spruce versus bogs according to both analyses is elevation (Table 3.5d). Fire interval is a strong driver for spruce forest when compared to either deciduous forest or bogs. Overall, t-values and standardized coefficients identified similar, ecologically significant drivers and seem to both be useful tools in analyzing model performance.

Table 3.5a: Parameter ranking for tundra versus forest

Parameters	**Standardized Coefficient Value**	**T-Value**
Elevation	11,752,480	91
Precipitation	33,895	76
S-N Aspect	-20,081	-22
Fire Interval	-9,984	0
E-W Aspect	425	1
Slope	16	36
Temperature	-6	-156
Intercept	-2	-241
Drainage	0	-51

Table 3.5b: Parameter ranking for deciduous vs. spruce forest

Parameters	Standardized Coefficient Value	T-Value
Fire Interval	-34,432,270	-69
Elevation	8,334,067	51
E-W Aspect	5,734	9
Precipitation	-3,768	-11
S-N Aspect	1,064	1
Slope	-14	-27
Intercept	-1	-138
Drainage	0	4
Temperature	0	1

Table 3.5c: Parameter ranking for black vs. white spruce

Parameters	Standardized Coefficient Value	T-Value
Fire Interval	-7,051,116	-22
Elevation	-1,501,024	-7
S-N Aspect	83,802	70
Precipitation	-25,319	-47
E-W Aspect	-2,883	-3
Slope	-52	-75

Intercept	1	162
Temperature	1	24
Drainage	0	30

Table 3.5d: Parameter ranking for spruce versus bog

Parameters	Standardized Coefficient Value	T-Value
Elevation	-18,172,670	-72
Fire Interval	2,474,785	8
S-N Aspect	-11,081	-6
E-W Aspect	3,903	3
Precipitation	-1,696	-2
Slope	-8	-10
Temperature	3	47
Intercept	3	214
Drainage	0	13

Another issue that can affect model performance is the correlation among predictors (Table 3.6), however only slope versus elevation and temperature versus precipitation have correlation values close to 0.5. Interior Alaska is characterized by flat areas at low elevations and steeper slopes at higher elevations. Since the 1km resolution is too coarse for local gradients, the correlation between the climate parameters reflects large-scale geographic patterns. Interior Alaska is dry and cold along its northern and eastern boundaries (Figure 3.4). Since only those four predictors show relatively strong correlations, overall model performance may not be affected.

Table 3.6: Correlation between regression predictors (values = 0.4 are in bold)

	Elevation	**S-N Aspect**	**E-W Aspect**	**Slope**	**Drainage**	**Temperature**
S-N Aspect	-0.094					
E-W Aspect	-0.005	-0.095				
Slope	**-0.465**	0.066	0.012			
Drainage	0.229	-0.019	-0.052	0.154		
Temperature	0.056	0.036	0.007	0.027	0.194	
Precipitation	0.085	-0.127	-0.039	-0.036	-0.176	**-0.571**

3.4.3 Model Validation

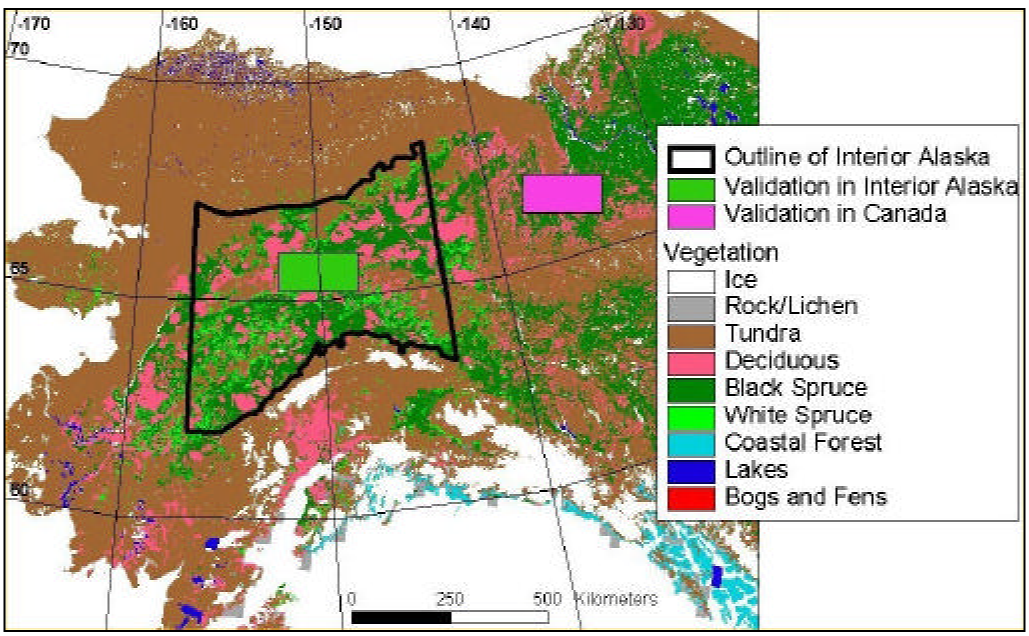
The logistic regression model was validated twice. Since the model was initially created solely in Interior Alaska, I first validated it for Interior Alaska. For this I created a 100km by 200km rectangular 'donut-hole' area in the center of Interior Alaska (Figure 3.7). I then recreated the logistic regression model for Interior Alaska using everything except the cells located in the 'donut hole.' The resulting equations and t-values were very similar to those derived from using all of Interior Alaska. The model could then be validated in the 'donut-hole.' The model was also validated in Northwestern Canada to test its applicability to an area outside Interior Alaska (Figure 3.7). I added bogs to the Canadian vegetation map using the same methods as for the Alaska data.

Model accuracy was good in both Interior Alaska and Northwestern Canada (Table 3.7). Accuracy even improved slightly for tundra versus forest predictions compared to the original model. Prediction accuracy for deciduous versus spruce vegetation declined to 53% in Canada from originally 68% but remained similar in Interior Alaska. Prediction accuracy for black versus white spruce declined by almost 10% in Interior Alaska (from 80% to 71%). Since there was no separate white spruce class in the vegetation classification for Canada, this vegetation type was not evaluated. Bogs were determined with very good accuracy in both Alaska (using spruce) and Canada (using black spruce only).

Table 3.7: Model validation

	Interior Alaska		NW Canada		Verification
Simulations	Accuracy (%)	Threshold	Accuracy (%)	Threshold	Accuracy (%)
Tundra vs. Forest	84	0.3	85	0.8	83
Dec. vs. Spruce	65	0.4	53	0.4	68
Black vs. White Spr.	71	0.5	(no white spruce class)		80
Spruce vs. Bog	96	0.8	89	0.3	93

Figure 3.7: Validation areas



3.4.4 Adding Actual Fire History to the Model

To test the effect of known fire history on overall model accuracy, time since the last fire was included as a predictor in the model in this separate exercise. Fire history is based on all recorded fires from 1950 to 1992 (the year of the remote sensing data used to establish the Fleming (1997) vegetation classification). Adding the fire history parameter improved the predictions for deciduous forest versus spruce forest (up from 68% accuracy to 85%) while the other predictions remained roughly the same (Table 3.8).

Table 3.8: Verification of model including fire history

Simulations	**Accuracy (%) (without fire)**	**Three most important predictors (t-value)**
Tundra vs. Forest	83 (83)	Temperature (-156), elevation (91), precipitation (77)
Dec. For. vs. Spruce	85 (68)	Last fire-year (-210), fire interval (-49), elevation (46)
Black vs. White Spr.	80 (79)	Slope (-75), S-N aspect (70), precipitation (-47)

3.5 Discussion

The logistic regression model provides geographically referenced locations of vegetation types in Interior Alaska, and it is able to predict vegetation with good overall accuracy (68% to 93%) from climate, topography, and fire data. The validation suggests that the model could be applied to other regions of boreal forest. While p-values and t-values flagged the same model parameters as significant, standardized regression coefficients and t-values identified slightly different ranking among drivers. Since the p-values were standardized to offset different ranges in model parameters, they may be more reliable indicators of model drivers.

Tundra seems to be strongly driven by elevation indicating mostly alpine tundra. Since the study region in Interior Alaska was chosen to exclude most of the latitudinal or coastal tundra this result would be expected. The standardized values indicate that south to north aspect was the third most important driver with a negative effect on tundra, suggesting that alpine tundra is mostly located at southern aspects with forest on northern aspects. This might be explained by moisture limitations for forests on southern exposures (Lloyd and Fastie 2002) or higher fire incidence on southern slopes due to higher temperatures and lower soil moisture (Bonan and Shugart 1989).

The distinction between deciduous and spruce forest was almost exclusively driven by fire history. Deciduous trees and shrubs establish first after a severe fire, while spruce requires several decades before it reaches the canopy (Viereck 1983, Van Wagner 1983). Model accuracy improved by almost 20% for deciduous versus spruce forest when actual fire history was added as a parameter. This confirms that fire regime is the most discriminating parameter for deciduous versus spruce forest. Deciduous forest appears earlier in the successional sequence than spruce forest (Viereck *et al.* 1983) and has a much longer period between fires than spruce forest (Rowe *et al.* 1974, Heinselman 1981).

Black and white spruce communities are differentiated by fire interval and elevation. According to the standardized coefficients, black spruce gives way to white spruce as fire interval increases and as elevation increases. Black spruce forests are characterized by higher fire frequency than white spruce forests due to their topographic location and tree structure (Viereck *et al.* 1986). When the Fleming (1997) vegetation classification was reduced to fewer classes, black spruce was assigned to bottomland spruce forests and northern aspects (Rupp, personal communication). In contrast, the timberline in Alaska is composed of white spruce (Lloyd and Fastie 2002). According to the t-values, slope and S-N aspect are important drivers, where black spruce prefers gentle slopes and northern aspects. In this case, slope and elevation represent similar environmental locations, as most flat bottomlands (at 1km resolution) are located at low elevations in Interior Alaska; These variables have a correlation value of -0.51 (Table 3.6c). The logistic regression model confirmed some of the rules used to create the WALE vegetation and recognized fire interval as the most important driver between black versus white spruce.

According to the USGS Land Cover Characteristics classification (Loveland *et al.* 1999), bogs are located mostly at elevations between 300m to 1000m in Interior Alaska. This was confirmed when elevation was identified as the most important driver in distinguishing bogs from spruce forest. Fire interval was identified as the second most important driver according to the standardized value, which might indicate that fire interval in general is a driver for spruce forest and not necessarily related to bogs. The t-values identify precipitation as a driver for spruce versus bog. The precipitation data set indicates a gradient of decreasing precipitation from southwest to northeast Interior Alaska. Northeast Alaska also contains the Yukon Flats, an extensive flat, boggy area. Since precipitation is the only gradient along this diagonal axis with a large bog on one end, the model might therefore identify precipitation as a driver.

The logistic regression model performed well during validation, predicting vegetation in northwestern Canada with almost the same accuracy as in Interior Alaska despite potential regional differences in vegetation. The model could potentially be applied to Scandinavia or Siberia after slight modifications to the vegetation types. Overall the logistic regression model for Interior Alaska performed well despite its simplicity. It was able to identify important ecological relationships among the environmental parameters and the vegetation types. The model seems accurate enough to be useful in exploring the complex response of the boreal forest in Alaska to climate and environmental change.

3.6 References

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Chapter 4 - Response of the four major vegetation types to changes in climate and fire interval

4.1 Abstract

Research from several disciplines recorded recent environmental changes at northern high–latitudes. So far increasing temperatures, increasing growing season length, and increasing precipitation have been reported, while changes in fire regime are yet unclear. To identify vegetation response to environmental change and its drivers in Interior Alaska, I imposed changes in temperature, precipitation, and fire interval on a hierarchical logistic regression model of the four major vegetation types found in this region. Environmental change was simulated with individual change parameters and also as simultaneous changes of two parameters. The landscapes resulting from coupled environmental changes were different from the individual change landscapes. Black spruce remained the dominant vegetation type under all scenarios expanding most under warming coupled with increasing fire interval. White spruce was clearly limited by moisture once average growing season temperatures exceeded a critical limit (2°C). Deciduous forests expanded their range the most when any two of the following scenarios were combined: decreasing fire interval, warming, and increasing precipitation. Tundra was replaced by forest under warming but expanded under precipitation increase. Model predictions agreed with current knowledge of the responses of vegetation types to

climate change but helped provide further insight into drivers of vegetation change. The response of vegetation types to environmental changes was clearly not linear when two changes were imposed simultaneously. Based on the Hadley CM2 climate prediction for 2100, Interior Alaska will shift towards more black spruce with some deciduous forest, while the extent of alpine tundra will be vastly reduced.

4.2 Introduction

Greenhouse gases released by human activities are the dominant forcing in anomalously high latter 20th century temperatures in the Northern Hemisphere, overriding a millennial-scale cooling trend due to astronomical forcing (Briffa *et al.* 1995, Mann *et al.* 1998, Mann and Bradley 1999). At northern high latitudes this results in winter and spring warming accompanied by increased terrestrial precipitation (Houghton *et al.* 1995, Serreze *et al.* 2000). Seemingly in response, total plant growth (as estimated from satellite data) from 45° to 70°N has increased between 1981 and 1999 in most of Eurasia, parts of Alaska, boreal Canada, and northeastern Asia (Myneni *et al.* 1997, Zhou *et al.* 2001). There are also several reports of increased shrubbiness at tree-line in northwest Alaska (Silapaswan *et al.* 2001), in the northern Alaskan tundra (Sturm *et al.* 2001), and at low elevations in high latitudes in northwestern North America (McKenzie *et al.* 2001). However, vegetation response to warming at high latitudes is complex, as increased warming does not lead to linear increases in vegetation biomass (Shaver *et al.* 2000). Vegetation response often lags behind climate change depending on disturbance regime and the ability of species to disperse and establish themselves (Davis 1989, Starfield and Chapin 1996, Camill and Clark 2000, Masek 2001). Climate change will also probably lead to new assemblages of plants (Kirilenko and Solomon 1998, Epstein *et al.* 2000) which might not be included in our current prediction models.

Soil moisture limitations in Interior Alaska could potentially lead to the formation of a novel steppe-like vegetation type (Rupp *et al.* 2000). Other indicators for warming induced moisture limitations are the recent decline of timberline white spruce in Alaska and northwest Canada (Szeicz and MacDonald 1995). This might explain the de-coupling noted between warming and tree-ring width indicating an overall decrease in tree ring width despite continued warming at high latitude sites in the Northern Hemisphere (Briffa *et al.* 1998, Vaganov *et al.* 1999, Barber *et al.* 2000, Lloyd and Fastie 2002). Warming has also caused large-scale permafrost degradation in Interior Alaska since the mid-1700s leading to ecosystem conversions from birch forests to fens and bogs (Jorgensen *et al.* 2001).

Disturbances in boreal forests are dominated by large-scale wildfires and insect outbreaks (Viereck and Schandelmeier 1980, Dyrness *et al.* 1986). Large scale wildfire plays a very important role in the boreal forest, as it clears the ground and removes insulating organic matter thereby improving seedling establishment and survival (Dyrness and Norum 1983, Zasada *et al.* 1987). There are many complex interactions among insect disturbance, fire, climate, and vegetation type. Warmer winters might lead to higher survival in insects which in turn could lead to larger outbreaks followed by stand-replacing fires (Volney and Fleming 2000). A high-resolution charcoal record for the past 7,000 years in Quebec indicates that climate, and not vegetation, controls the long-term fire regime in the boreal forest (Carcaillet *et al.* 2001). However, when groundwater level was decreased during the medieval warming period in Alberta, birch was replaced with less fire-prone aspen leading to a decrease in fire frequency (Campbell and Campbell 2000). Both long-term climate and landscape properties (such as topography and soil moisture) have a strong impact on the distribution and dynamics of boreal vegetation; however, while climate controls fire regime at the regional scale, landscape interactions predominate the local scale (Bergeron 1991). Other research in Quebec indicates that a severe fire regime at the northern tree line can turn a boreal forest area into tundra (Sirois and Payette 1991, Arsenault and Payette 1997). On the other hand, lake charcoal levels in Interior Alaska indicate that when boreal forest established itself ca. 9,000 to 7,500 years ago, fire frequency was very high (Earle *et al.* 1996). A decline in fire frequency in recent years was noted for the boreal forest region in Eastern Canada, where warming seems to be offset by increased precipitation (Bergeron and Archambault 1993, Carcaillet *et al.* 2001). Model predictions suggest that Central Canada should experience increased fire frequency (Flannigan *et al.* 2001); however, one study found that fire frequency has decrease in central Saskatchewan between 1831 and 1995 (Johnson *et al.* 1999). In Western Canada and Alaska fire frequency can be expected to increase due to warming (Flannigan *et al.* 1998, Rupp *et al.* 2000).

The boreal forest of Alaska is located in the state's Interior between the Alaska Range in the south, the coastal tundra to the West, the Brooks Range to the North, and continues eastward into Canada. This study evaluates the equilibrium response of the four major vegetation types of Interior Alaska (black spruce, white spruce, deciduous forest, and tundra) to changes in growing season temperature, growing season precipitation, and fire interval using a logistic regression model. The chapter addresses the following questions:

1. How do the four major vegetation types in Interior Alaska respond to changes in temperature and precipitation?

2. How do the four major vegetation types in Interior Alaska respond to changes in fire regime?
3. How do the four major vegetation types in Interior Alaska respond to simultaneous changes in fire interval, precipitation, and temperature?
4. What will be the potential vegetation distribution in Interior Alaska in 2100?

4.3 Methods

The response of the four major vegetation types (tundra, deciduous forest, black spruce forest, and white spruce forest) in Interior Alaska to changes in mean growing season temperature, total growing season precipitation, and fire interval was investigated using a logistic regression model. This model predicts the occurrence of the four vegetation types using elevation, aspect, slope, average growing season (May through September) temperature, total growing season precipitation, soil drainage, and fire interval. The logistic regression model for Interior Alaska and all input data sets are described in detail in the previous chapter. For all climate and fire interval change simulations, input predictors were altered homogeneously, before the model simulated equilibrium vegetation under these new conditions. Here the term ‘fire interval’ describes the number of years between burns in an individual pixel. Since logistic regression differentiates between only two possible outcomes the model is run in three steps (Figure 4.1). Present vegetation is based on a model simulation using Climate Research Unit (CRU) climate averages from 1960-1990 (New *et al.* 1999) and fire interval data (Matt

Macander, unpublished data) interpolated from the historic Alaska fire record (Murphy *et al.* 2000).

Figure 4.1: Three steps of the logistic regression model for Interior Alaska

1.+ Tundra or

+ Forest - > 2. + Deciduous forest or

+ Spruce forest - > 3. + Black spruce forest or

+ White spruce forest

A total of 48 different scenarios of environmental change were performed. Temperature was increased by 1°C, 2°C, 5°C, and 10°C. Precipitation was both increased and decreased by 10%, 20%, and 30%. All these temperature and precipitation scenarios were combined into 24 different scenarios for coupled climate change. Fire interval was both increased and decreased by 10%, 20%, and 30%. An increase in fire interval represents a lengthening of the time between fires, allowing vegetation more time to recover between disturbances. Fire interval was combined with warming into four scenarios: fire interval could increase or decrease by 30%, and temperature could rise by 5°C or 10°C. Fire interval was also combined with precipitation into four scenarios: fire interval could increase or decrease by 30%, while precipitation could increase or decrease by 30%.

These 48 climate change scenarios are not based on expectations for future climate in Interior Alaska but serve more or less as model sensitivity tests. To get a more realistic picture of what vegetation in Interior Alaska might look like in 2100, the logistic regression model was run using transient climate simulations from the UK Hadley Center CM2 model (Johns *et al.* 1997). This model predicts future climate based on the combined effects of changes in greenhouse gases and sulphate aerosols. The Hadley predictions for 2100 were super-imposed on the current climate file.

4.4 Results: Response to Climate Change Simulations

4.4.1. Temperature Change

Tundra disappears when present temperatures increase by more than 5°C (Table 4.1). The extent of white spruce increases at +1°C and +2°C but decreases when temperatures continue to rise. Deciduous forest and black spruce forest, on the other hand, continue to expand with rising ambient temperatures. Based on the degree of change for each vegetation type - the area covered under a climate change scenario as a proportion of the area covered under current climate - the four vegetation types can be arranged according to how strongly they respond (in a relative rather than absolute way) to this particular environmental change, and if they respond in a positive or negative manner (Figure 4.2). The area currently covered by tundra decreases more than the area covered by white spruce, while the area of deciduous forest increases more than the area for black spruce. White spruce is the only vegetation type that does not display a strong linear relationship with temperature increase (Table 4.1); instead it shows a non-linear response to increasing temperatures. Under 10°C warming over current temperatures, deciduous forests expands to roughly 450% of their current distribution, completely replacing tundra and reducing white spruce forests to less than 50% of their current range. Black spruce forest also benefits from 10°C warming, increasing its extent by 135% over its current distribution. At 10°C warming, both tundra and white spruce forest are replaced by black spruce forest (Table 4.2).

Table 4.1: Vegetation distribution under temperature increase (in percent)

	Present	**1°C**	**2°C**	**5°C**	**10°C**
Tundra	23	14	8	0	0
Decid. Forest	1	2	3	5	5
Black Spruce	67	74	79	86	92
White Spruce	9	10	11	9	4

Figure 4.2: Relative response of vegetation to 10°C warming

Tundra White Spruce	Black Spruce Deciduous Forest
← Vegetation Type Decrease	Vegetation Type Increase →

Table 4.2: Replacement of vegetation types at 10°C warming

Present Vegetation	**New Vegetation**

Tundra	69 % Black Spruce 16 % Deciduous Forest 14 % White Spruce
Deciduous Forest	99 % Deciduous Forest 1 % Black Spruce
Black Spruce	100 % Black Spruce
White Spruce	96 % Black Spruce 4 % White Spruce

4.4.2 Precipitation Change

All four vegetation types show a strong response to precipitation change (Table 4.3). Both tundra and white spruce increase to almost 150% of their current distribution under 30% precipitation increase. Deciduous forest decreases to 34% of its current distribution under the same precipitation increase, while black spruce decreases to 75%. Precipitation decrease leads to the opposite result: a doubling in deciduous forest and a slight increase in black spruce. White spruce and tundra decrease to 54% and 67%, respectively, of their current ranges. The vegetation types could be arranged along a precipitation gradient where deciduous forest and tundra are at opposite ends (Figure 4.3). Under 30% precipitation increase, approximately 50% of the areas currently covered by either deciduous forest or white spruce were converted to tundra (Table 4.4). Precipitation decrease led to an invasion of black spruce into former tundra and white spruce forest.

Table 4.3: Vegetation distribution under precipitation changes (in percent)

	-30%	-20%	-10%	Present	+10%	+20%	+30%
Tundra	15	17	20	23	26	31	35
Dec. For.	2	2	1	1	1	1	0
Black Spr.	78	75	72	67	62	57	51
White Spr.	5	6	7	9	11	12	13

Figure 4.3: Relative response of vegetation to 30% precipitation increase

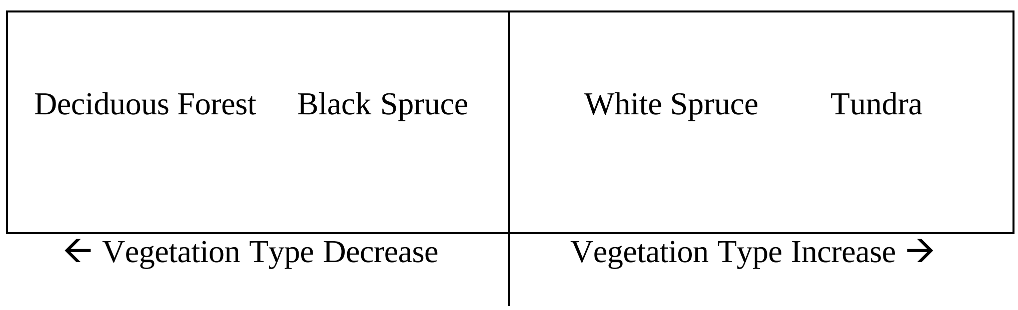


Table 4.4: Replacement of vegetation types under precipitation changes

Present Vegetation	**Vegetation at +30% precipitation**	**Vegetation at -30% precipitation**
Tundra	100% Tundra	67% Tundra 22% Black Spruce 8% White Spruce 3% Deciduous Forest
Deciduous Forest	50% Tundra 34% Deciduous Forest	100% Deciduous Forest

	15% Black Spruce 1% White Spruce	
Black Spruce	75% Black Spruce 13% White Spruce 12% Tundra	99% Black Spruce 1% Deciduous Forest
White Spruce	52% White Spruce 48% Tundra	67% Black Spruce 32% White Spruce

4.4.3 Simultaneous Temperature and Precipitation Change

When changes of temperature and precipitation are combined, one factor typically drives the vegetation change more than the other, indicating which is the stronger driver in the simulation scenario. Vegetation changes across the precipitation gradient are no longer linear when interacted with temperature increases. Under the combined warming and precipitation change scenarios, deciduous forest has the greatest relative increase (Table 4.5). At 10°C warming and precipitation decrease by 30%, deciduous forest expands to 554% of its current range; while 30% precipitation increase leads to deciduous forest expansion to 389% of its current range. Tundra is eliminated when temperatures reach or exceed 5°C regardless of the precipitation regime, though its decline is accelerated under drier conditions. Black spruce increases slightly with warming when precipitation decreases simultaneously; precipitation however is the stronger driver for black spruce change. When precipitation increases with warming, black spruce responds best at high temperature increases (>5°C) and low precipitation increases (10%). White spruce displays a constant decline with coupled warming and precipitation decrease (Figure 4.4). This decline is hastened with greater reductions in precipitation. However, if precipitation increases with temperature, white spruce expands to roughly twice its current distribution at 1°C, 2°C and 5°C warming but declines below its current distribution at 10°C warming. Vegetation type response to the most extreme coupled temperature (10°C warming) and precipitation change (30% increase) produces essentially the same results as warming by itself (compare Figure 4.5 with Figure 4.2). This indicates that temperature has a more direct influence than precipitation in these scenarios. Black spruce is the main invader into all vegetation types under precipitation increase with warming (Table 4.6). It is also the main invader into tundra and white spruce forest under precipitation decrease with warming.

Table 4.5: Vegetation under simultaneous temperature and precipitation change

1°C Warming	**Precipitation Change**						
	-30%	**-20%**	**-10%**	**Present**	**+10%**	**+20%**	**+30%**
Tundra	9	11	12	23	16	18	21
Decid. Forest	3	3	2	1	1	1	1
Black Spruce	82	80	77	67	70	65	60
White Spruce	5	7	8	9	13	15	18

2°C Warming	Precipitation Change						
	-30%	-20%	-10%	Present	+10%	+20%	+30%
Tundra	5	6	7	23	9	11	12
Decid. Forest	4	4	3	1	2	2	2
Black Spruce	85	84	82	67	75	71	67
White Spruce	6	7	9	9	13	16	20

5°C Warming	Precipitation Change						
	-30%	-20%	-10%	Present	+10%	+20%	+30%
Tundra	0	0	0	23	1	1	1
Decid. Forest	6	5	5	1	4	4	4
Black Spruce	90	89	88	67	84	82	79
White Spruce	5	6	7	9	11	13	17

10°C Warming	Precipitation Change						
	-30%	-20%	-10%	Present	+10%	+20%	+30%
Tundra	0	0	0	23	0	0	0
Decid. Forest	6	5	5	1	4	4	4
Black Spruce	93	92	92	67	91	90	89
White Spruce	2	2	3	9	5	6	7

Figure 4.4: Total area covered by white spruce in response to coupled warming and precipitation changes

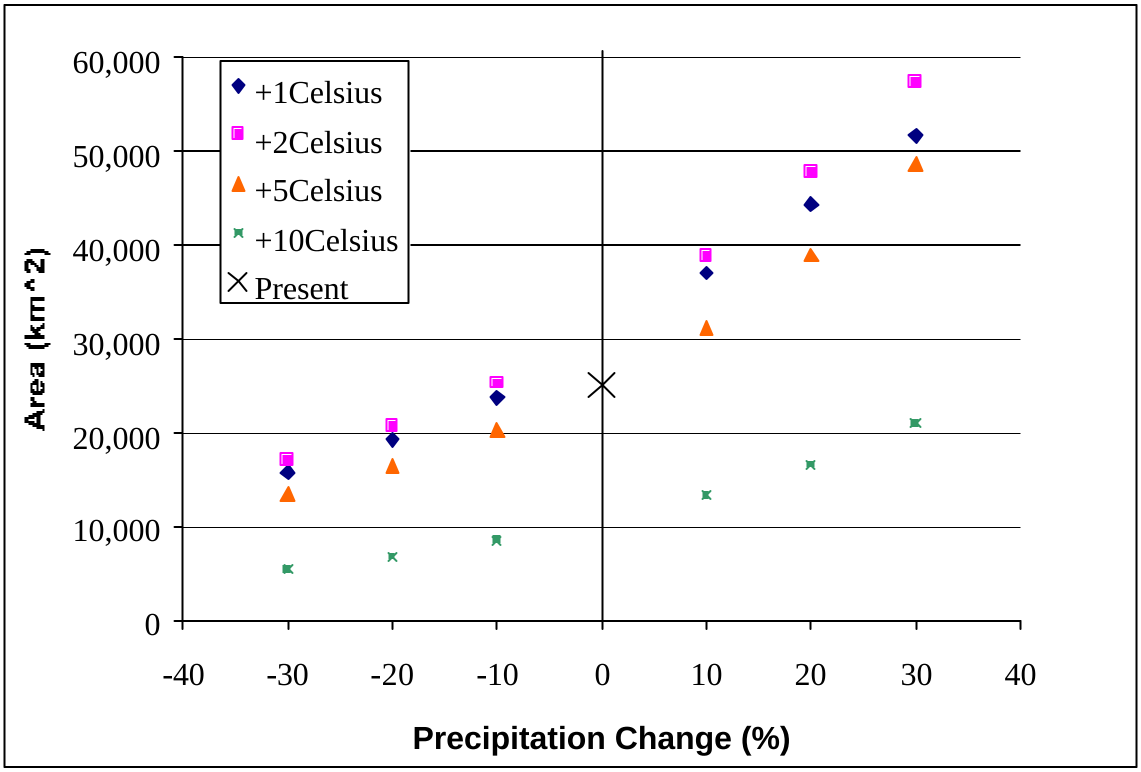


Figure 4.5: Relative response of vegetation to simultaneous 10°C warming and 30% precipitation increase

Tundra	White Spruce	Black Spruce	Deciduous Forest

← Vegetation Type Decrease | Vegetation Type Increase →

Table 4.6: Replacement of vegetation types under simultaneous temperature and precipitation change

Present Vegetation	Vegetation at +30% ppt & +10°C	Vegetation at –30% ppt & +10°C
Tundra	61% Black Spruce 25% White Spruce 14% Deciduous Forest	74% Black Spruce 18% Deciduous Forest 8% White Spruce
Deciduous Forest	71% Deciduous Forest 29% Black Spruce	100% Deciduous Forest
Black Spruce	100% Black Spruce	99% Black Spruce 1% Deciduous Forest
White Spruce	82% Black Spruce 18% White Spruce	99% Black Spruce 1% White Spruce

4.4.4 Changes in Fire Interval

When fire interval lengthens by 30% over current levels, white spruce expands to 110% of its current area, while deciduous forest shrinks to 43% of its current area (Table 4.7). When fire interval decreases, deciduous forest increases to 233% of its current distribution, while white spruce decreases to 90% of its current area. Tundra and black spruce vegetation remain essentially stable through all six fire interval scenarios. Aligning the four major vegetation types along a fire interval gradient shows deciduous forest and white spruce forest at the two ends of decreasing and increasing area, respectively, while tundra and black spruce forest remain constant (Figure 4.7). Black spruce is the main invader into deciduous forest under fire interval increase and the main invader into white spruce under fire interval decrease (Table 4.8).

Table 4.7: Vegetation under changes in fire interval

	-30%	-20%	-10%	Present	+10%	+20%	+30%
Tundra	23	23	23	23	23	23	23
Decid. Forest	2	2	1	1	1	1	0
Black Spruce	67	67	67	67	68	67	67
White Spruce	8	8	8	9	9	9	10

Figure 4.6: Relative response of vegetation types to increase in fire interval

Deciduous Forest	Tundra Black Spruce	White Spruce
← Vegetation Type Decrease	No Change	Vegetation Type Increase →

Table 4.8: Replacement of vegetation types under changes in fire interval

Present Veg.	Vegetation at +30% FI	Vegetation at -30% FI
Tundra	100% Tundra	100% Tundra
Deciduous Forest	53% Black Spruce 43% Deciduous Forest 3% White Spruce	100% Deciduous Forest
Black Spruce	99% Black Spruce 1% White Spruce	98% Black Spruce 2% Deciduous Forest
White Spruce	100% White Spruce	90% White Spruce 8% Black Spruce 1% Deciduous Forest

4.4.5 Simultaneous Fire Interval Change and Warming

Regardless of the warming rate and fire interval change, tundra disappears from Interior Alaska in all four scenarios (Table 4.9). White spruce also disappears almost completely under all four scenarios. Fire interval increase by 30% with 5°C warming reduces white spruce to 28% of its current distribution which is the largest extent of this vegetation type under all scenarios. Black spruce increases its current range to 128% to 148% under all four scenarios. Deciduous forest expands its area by 1169% under decreasing fire interval and by 467% under increasing fire interval. The higher the temperature, the more deciduous forest is able to expand. The four vegetation types could be arranged according to which environmental change combination in these four scenarios allowed for the largest expansion in area (Figure 4.7). Black spruce invades both tundra and white spruce under 10°C warming and fire interval increase and decrease (Table 4.10).

Table 4.9: Fire interval change (FI) and warming by 5°C and 10°C

	Present	+5°C & -30% FI	+10°C & -30% FI	+5°C & +30% FI	+10°C & +30% FI
Tundra	23	0	0	0	0
Decid. Forest	1	12	12	4	5
Black Spruce	67	87	88	94	95
White Spruce	9	1	1	2	0

Figure 4.7: Preferred environmental change for the four vegetation types

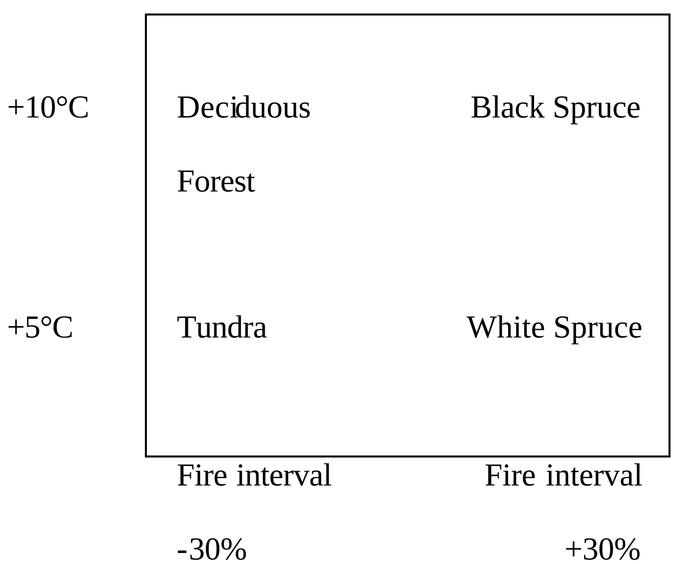


Table 4.10: Replacement of vegetation types under simultaneous fire interval change and warming

Present Vegetation	Vegetation at +30% FI & +10°C	Vegetation at -30% FI & +10°C
Tundra	83% Black Spruce 13% Deciduous Forest 4% White Spruce	64% Black Spruce 33% Deciduous Forest 2% White Spruce
Deciduous Forest	64% Deciduous Forest 36% Black Spruce	100% Deciduous Forest
Black Spruce	100% Black Spruce <1% Deciduous Forest	96% Black Spruce 4% Deciduous Forest
White Spruce	99% Black Spruce 1% Deciduous Forest	94% Black Spruce 6% Deciduous Forest

4.4.6 Simultaneous Fire Interval and Precipitation Changes

White spruce basically disappears under all four fire interval/precipitation change scenarios (Table 4.11). Tundra decreases under precipitation decrease but increases its range under precipitation increase regardless of fire interval. Black spruce remains stable under precipitation increase and expands its range under precipitation decrease; especially when fire interval increases as well. Deciduous forest shows the most varied response to the four scenarios ranging from a decrease to 36% of its current distribution under both fire interval and precipitation increase to expansion to 832% of its current distribution when both precipitation and fire interval decrease.

Arranging the four vegetation types by their most beneficial scenario displays a similar distribution by fire interval when interacted with temperature changes (Figure 4.8). White and black spruce once again prefer increased fire interval, while tundra and deciduous forest benefit from decreased fire intervals. In all four scenarios, the largest invader into tundra is black spruce (Table 4.12). Tundra remains essentially stable under higher fire frequency and wetter conditions and successfully invades all other vegetation types whenever precipitation increases regardless of fire interval. White spruce is almost completely replaced by black spruce under all four scenarios.

Table 4.11: Fire interval change (FI) and precipitation change (ppt)

	Present	**-30% FI & +30% ppt**	**-30% FI & -30% ppt**	**+30% FI & +30% ppt**	**+30% FI & -30% ppt**
Tundra	23	30	14	30	13
Decid. Forest	1	2	8	0	2
Black Spruce	67	66	78	68	84
White Spruce	9	1	0	2	1

Figure 4.8: Preferred environmental change for the four vegetation types

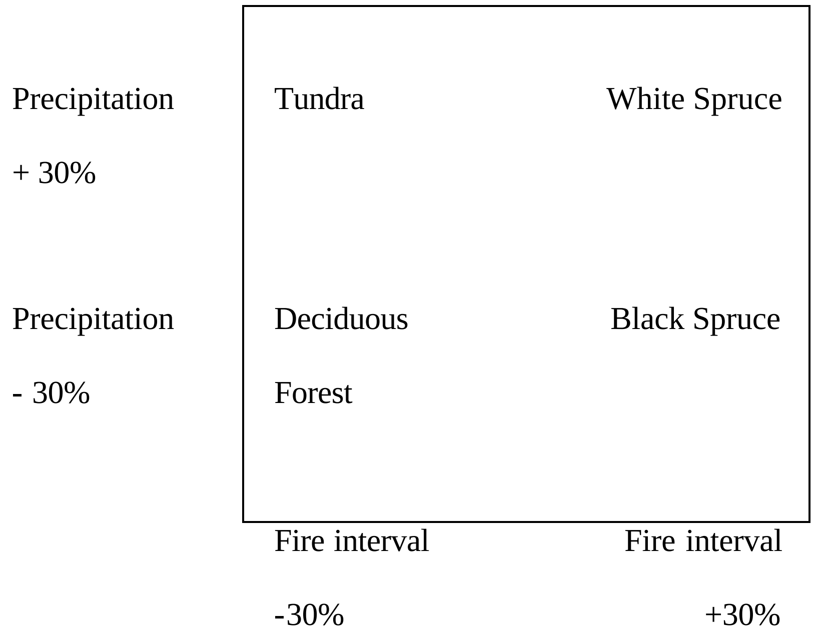


Table 4.12: Replacement of vegetation types under fire interval and precipitation changes

Present Vegetation	-30% FI & -30% ppt	-30% FI & +30% ppt	+30% FI & -30% ppt	+30% FI & +30% ppt
Tundra	59% Tundra 28% Black Spr. 11% Dec. For. 1% White Spr.	99% Tundra	58% Tundra 36% Black Spr. 4% Dec. For. 2% White Spr.	99% Tundra 1% Black Spr.
Deciduous Forest	100% Dec. For.	61% Dec. For. 39% Tundra	78% Dec. For. 22% Black Spr.	38% Tundra 32% Dec. For. 30% Black Spr.

Black Spruce	94% Black Spr. 6% Dec. For.	88% Black Spr. 9% Tundra 2% Dec. For. 1% White Spr.	100% Black Spr.	90% Black Spr. 9% Tundra 1% White Spr.
White Spruce	90% Black Spr. 8% Dec. For. 2% White Spr.	76% Black Spr. 15% Tundra 6% White Spr. 3% Dec. For.	96% Black Spr. 3% White Spr. 1% Dec. For.	78% Black Spr. 15% Tundra 7% White Spr.

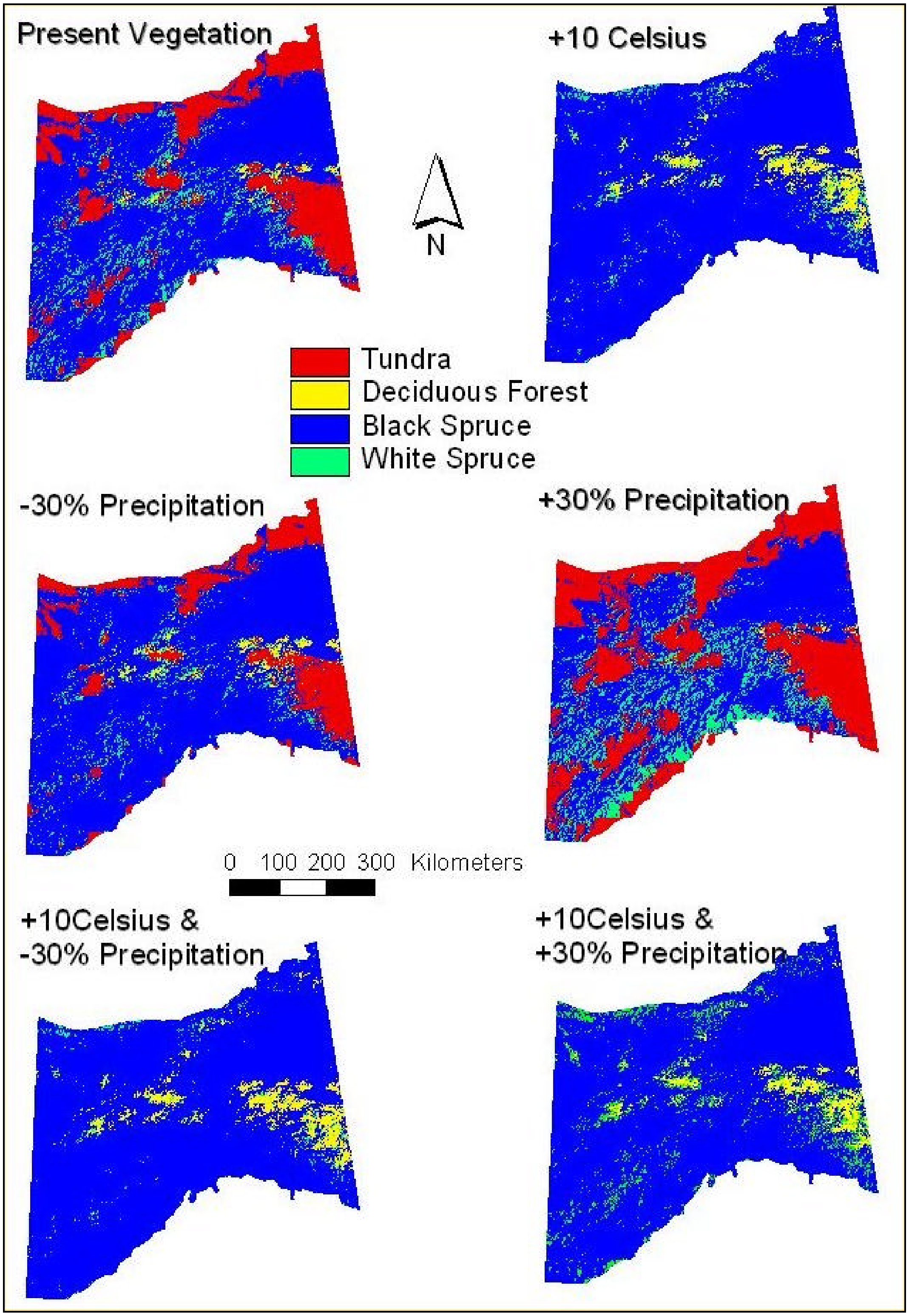
4.4.2 Areas sensitive to change on the landscape scale

Warming by 10°C leads to a replacement of the current vegetation types in 31% of Interior Alaska. In this scenario, higher elevations serve as refuges for deciduous forest and white spruce while black spruce remains in flat areas below ca. 500m (Figure 4.9). Increasing precipitation results in a change in vegetation type in 22% of the area, compared to a 14% change caused by decreasing precipitation. Changes in fire interval cause negligible vegetation type replacement.

When 10° warming is imposed, areas of change are concentrated at 200 to 800m (72% of the area of change), N and W aspect (64%), and 1 to 8% slope (65%). Seventy-four percent of the area of change was originally covered by tundra. On visual interpretation, landscapes resulting from 10° warming or 10° warming coupled with either precipitation or fire interval changes, look similar indicating that 10°C warming drives the vegetation response (Figure 4.9).

Similarities between landscapes can be statistically determined using kappa values (Congalton *et al.* 1983, Erratum Photogrammetric Engineering and Remote Sensing 50(10):1477). When comparing the landscape resulting from 10°C warming, 30% precipitation increase, and the scenario where these two factors are coupled, kappa values indicate 'substantial' (Landis and Koch 1977) similarities between warming versus the coupled scenario compared to 'slight' agreements between warming versus precipitation increase or precipitation increase versus the coupled simulation (Figure 4.10). Kappa values confirm statistically that warming drives the vegetation response when 10°C warming is coupled with (30%) precipitation increase, fire interval increase, or fire interval decrease. When landscapes resulting from individual and combined precipitation and fire interval changes are compared, kappa values are in the 'moderate' to 'substantial' range. Precipitation decrease seems to be a slightly stronger driver than fire interval in the combined simulation. Based on the kappa statistics, fire interval decrease is a stronger driver than precipitation decrease, while precipitation increase is a slightly stronger driver than fire interval increase.

Figure 4.9: Maps of vegetation type changes in Interior Alaska



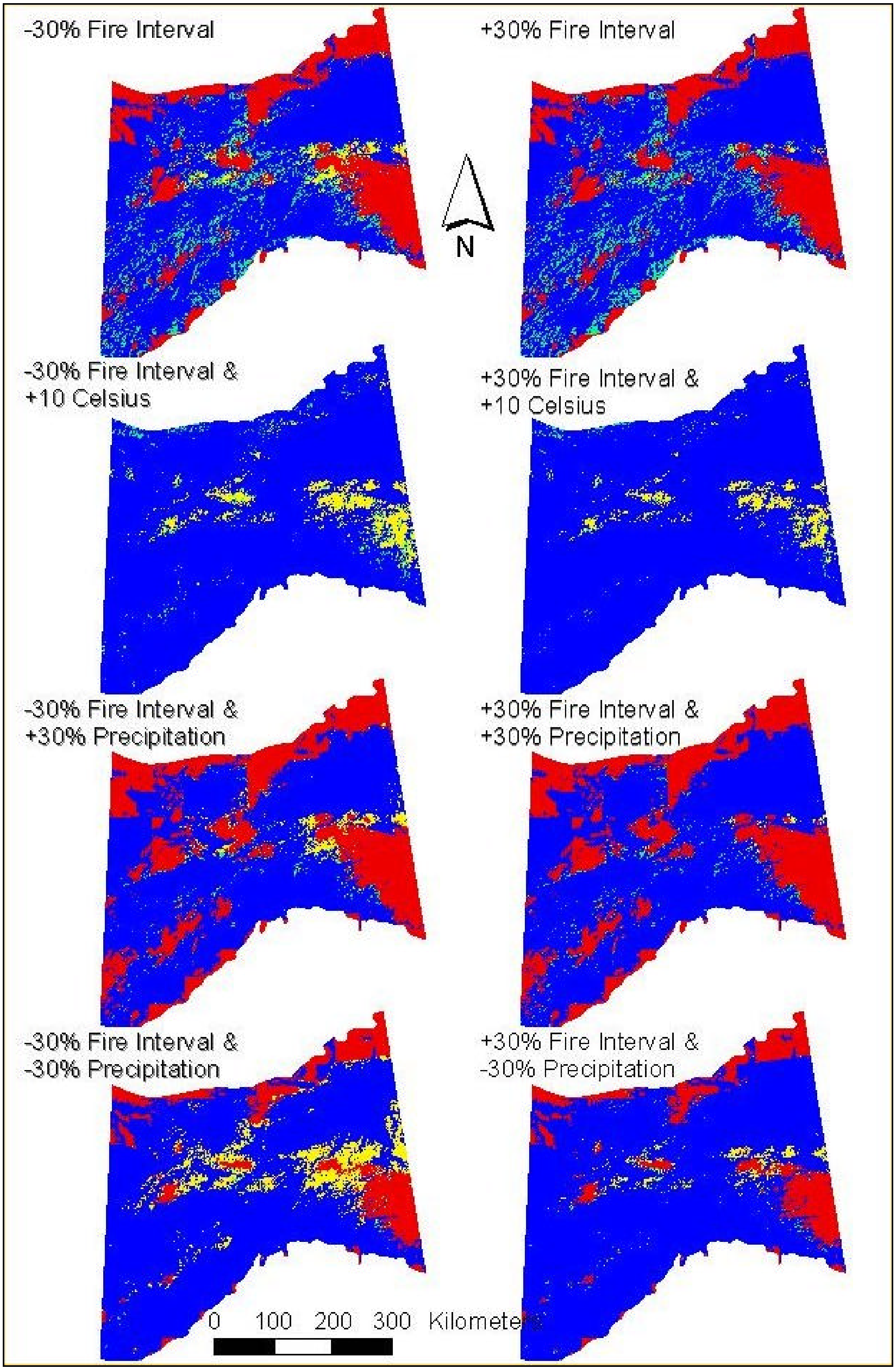
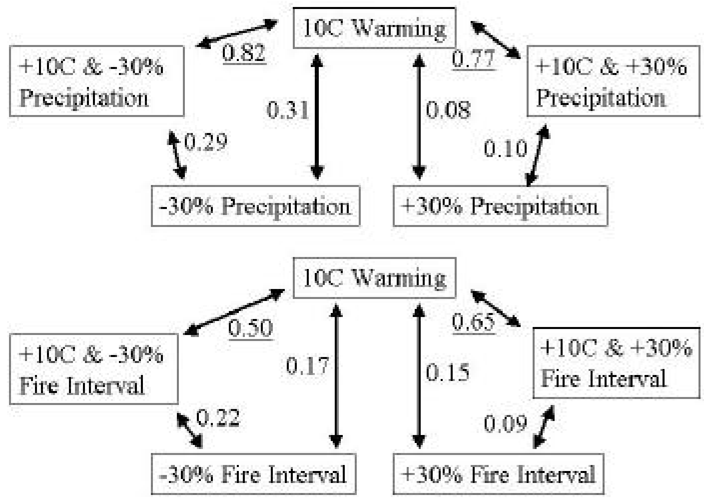
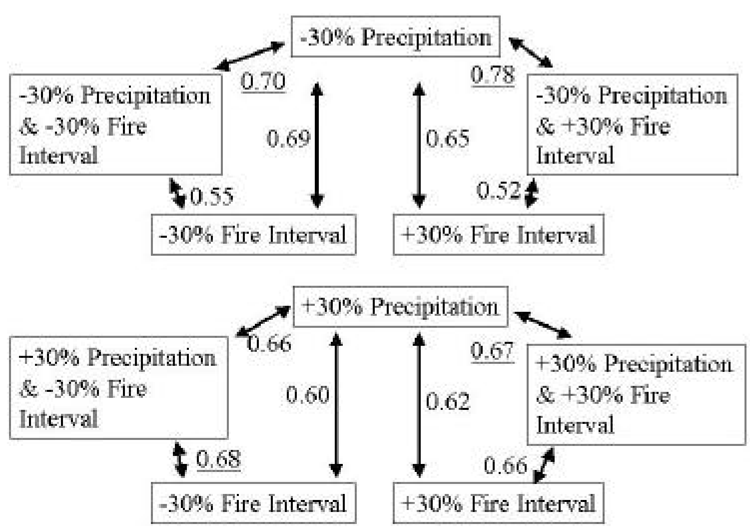

-30% Fire Interval
+30% Fire Interval
N
-30% Fire Interval &
+10 Celsius
+30% Fire Interval &
+10 Celsius
-30% Fire Interval &
+30% Precipitation
+30% Fire Interval &
+30% Precipitation
-30% Fire Interval &
-30% Precipitation
+30% Fire Interval &
-30% Precipitation
0 100 200 300 Kilometers

Figure 4.10: Kappa values comparing change simulations (highest value is underlined)



Interpretation of Kappa values (Landis and Koch, 1977):

Kappa Statistic	Strength of Agreement
<0.00	Poor
0.00-0.20	Slight
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Substantial
0.81-1.0	Almost Perfect



4.4.8 Hadley climate prediction for 2100

The Hadley CM2 model (Johns *et al.* 1997) predicted a 6% precipitation increase for basically all of Alaska accompanied by 1 to 5°C warming (Figure 4.11). The average temperature increase for Interior Alaska by 2100 will be 2.8°C. The potential vegetation distribution under this scenario creates a landscape consisting mostly of black spruce forest with some deciduous forest and very little white spruce at intermediate elevations, and tundra at high elevations (Figure 4.12). Under these conditions, black spruce can expand to 89% of Interior Alaska, while deciduous forest and white spruce both increase from 1% to 5% and 2% respectively (Table 4.13). All three vegetation types replace tundra which decreases drastically from 23% to only 2% of Interior Alaska. Black spruce not only invades more than half of the area currently covered by tundra, but it also almost completely takes over the sites that currently support white spruce (Table 4.14). White spruce, in turn can only invade tundra sites. Deciduous forest mostly invades current tundra sites. The alpine tundra on low elevation hills in the center of Interior Alaska is replaced by deciduous forest (Figure 4.12).

Figure 4.11: Hadley temperature prediction for Alaska in 2100

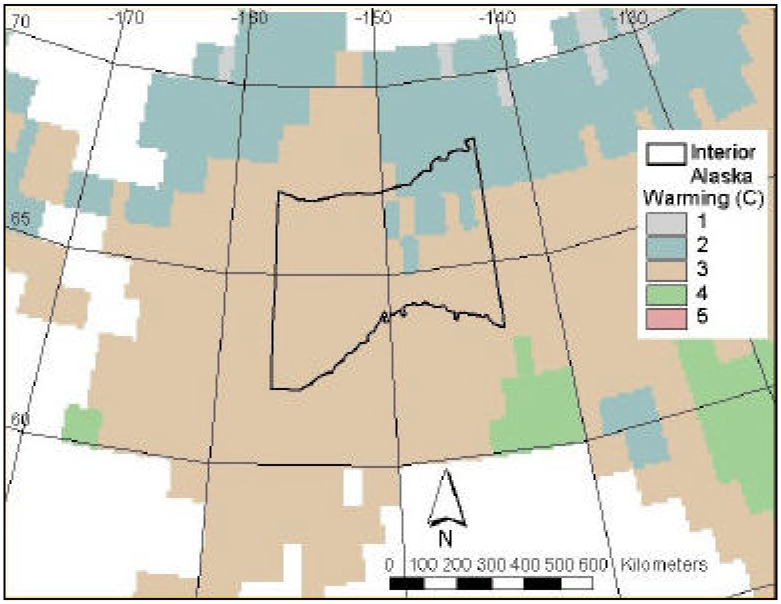


Figure 4.12: The vegetation in Interior Alaska present and future

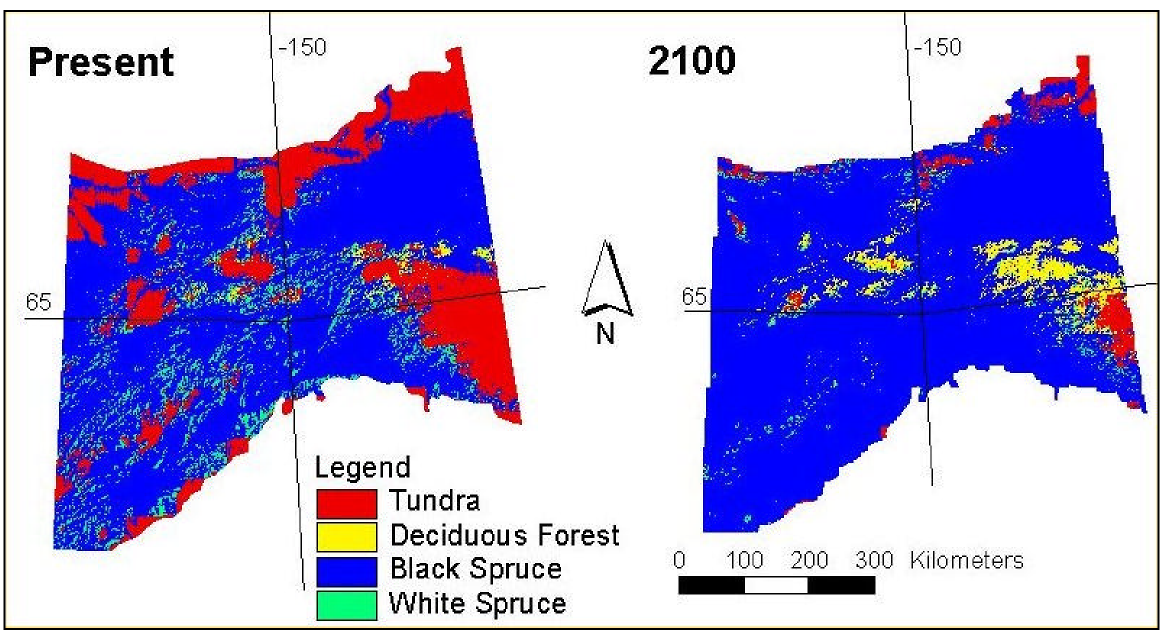


Table: 4.13: Present vegetation distribution versus potential vegetation distribution under the Hadley climate scenario for the year 2100

	Present	**+average of 2.8°C & +6% precipitation**
Tundra	23	2
Deciduous Forest	1	5
Black Spruce	67	89
White Spruce	9	2

Table 4.14: Replacement of vegetation types under the Hadley scenario

Present Vegetation	**Vegetation in 2100**
Tundra	18% Tundra 15% Deciduous Forest 55% Black Spruce 9% White Spruce
Deciduous Forest	97% Deciduous Forest 2% Black Spruce
Black Spruce	1% Deciduous Forest 99% Black Spruce
White Spruce	2% Deciduous Forest 93% Black Spruce 4% White Spruce

4.5 Discussion

Warming generally improves tree growth in the temperature-limited boreal zone (Grossnickle 2000); however, warming-induced soil moisture deficit is becoming detrimental to white spruce (Szeicz and MacDonald 1995, Barber *et al.* 2000). In northern Manitoba, net primary productivity (NPP) has increased between 1900 and 1990, while southern Saskatchewan experienced a drastic reduction of woody biomass and a conversion of boreal forest to grassland, which was attributed to temperature-induced moisture stress (Peng and Apps 1999, Price *et al.* 1999). Simulations with both the CENTURY model and FORSKA2 indicated that boreal forest vegetation was very sensitive to changes in precipitation (Price *et al.* 1999). My logistic regression model also identifies a reduction in white spruce with increasing temperatures, while the other forest types continue to expand, indicating that black spruce and deciduous forest might not be moisture limited.

Black spruce forest currently dominates Interior Alaska, accounting for 68% of the simulated vegetation. Regardless of the climate scenario, black spruce always remains the most dominant vegetation type. Comparing all 48 scenarios, black spruce is most successful under 30% increase in fire interval with 10°C warming, where it can expand to 95% of Interior Alaska. It decreases to only 51% of Interior Alaska under 30% precipitation increase. Black spruce expands most under warming but also under decreasing precipitation, and it does not respond to changes in fire interval by itself. When decreasing precipitation and warming are combined, they lead to roughly the same vegetation extent as warming alone. Warming also offsets the detrimental effect of increased precipitation leading to an overall increase in black spruce under a coupled scenario. The two responses indicate that 10°C warming might be a stronger driver than 30% precipitation change for black spruce. This is in contrast to gap model simulations for forests near Fairbanks that indicate the best growing conditions for upland black spruce are 3°C warming with increased precipitation by 60% (Bonan *et al.* 1990b). This model simulates biomass not areal extent like the logistic regression model. The authors found that warming-induced reductions in soil moisture reduce soil conductivity which in turn lowers soil temperatures. This cycle can be offset by increased precipitation which improves growing conditions for black spruce (Bonan *et al.* 1990a). Simulations in central Canada's southern boreal zone produce a decline in black spruce with monthly precipitation decrease (Price *et al.* 1999), confirming Bonan *et al*.'s (1990) results. The coarse-scale precipitation input into the logistic regression model cannot capture soil moisture balance in the boreal forest.

Although black spruce extent does not respond to fire interval alone, it increases when fire interval change is combined with warming or precipitation change. When fire interval increases with warming, black spruce expands more than when warming only is imposed. Under fire interval decrease with warming, black spruce expands less than when warming occurs by itself. This is corroborated by simulations in northwest Alaska where warming led to an increase in the number and size of fires and resulted in a conversion of spruce to deciduous forest (Rupp *et al.* 2000).

Alpine tundra is the second most dominant vegetation type in Interior Alaska accounting for 23% of the simulated landscape. Tundra expands under only two scenarios: precipitation increase and precipitation increase coupled with fire interval change. It reaches its largest extent of 35% of the vegetation in Interior Alaska under 30% precipitation increase. The large-scale climate data used for the model is independent of the effect of elevation (see Figures 3.4 and 3.5), and I cannot explain why tundra responds positively to increases in precipitation. Tundra does not respond to changes in fire interval alone and responds the same to climate change (precipitation or temperature) coupled with either fire interval increase or decrease. Tundra seems very clearly driven by temperature and precipitation, with temperature as the stronger driver. Tundra disappears from Interior Alaska whenever warming is imposed; this trend is not offset by increasing precipitation. Even though it is not yet possible to detect advances in elevational tree-line with 79m pixel size Landsat images (Masek 2001), shrub invasion into arctic tundra has been noticed on aerial photographs (Sturm *et al.* 2001) and with 30m resolution Landsat Thematic Mapper images (Silapaswan *et al.* 2001). Warming experiments at Toolik Lake, Alaska, resulted in enhanced shrub production with decreases in non-vascular plants (Chapin *et al.* 1995). The conversion of tundra to spruce and deciduous forest under warming climate has been simulated in several studies (Starfield and Chapin 1996, White *et al.* 2000, Rupp *et al.* 2000, Rupp *et al.* 2001) however there is no indication that increased precipitation leads to more tundra.

White spruce accounts for 9% of the vegetated landscape in Interior Alaska. This vegetation type does not seem resistant to any environmental change, as it decreases under most of the 48 scenarios. White spruce increases only with warming up to 2°C, with precipitation increase, and with fire interval increase. White spruce expands to almost 20% of Interior Alaska under 2°C warming and 30% increase in precipitation. The response of white spruce to warming is not linear: it increases its area until 2°C warming but decreases when temperatures continue to rise. Combined precipitation and temperature increases result in larger expansion of white spruce than separate change scenarios. Thus white spruce can expand its range under moderate warming, especially if this warming is combined with increasing precipitation. But heat or probably moisture stress eventually limit white spruce growth, which is supported by field observations along the Alaskan timberline (Szeicz and MacDonald 1995, Barber *et al.* 2000, Lloyd and Fastie 2002). In simulations by Bonan *et al.* (1990), white spruce could only grow successfully at 1°C warming, while under the 3°C and 5°C climatic warming none of the tree species currently found in the typical white spruce-hardwood forest uplands of interior Alaska were able to grow due to soil moisture limitations. Even with 60% precipitation increase, white spruce experienced moisture limited conditions (Bonan *et al.* 1990b). In the logistic regression simulations, white spruce disappears from Interior Alaska when fire interval increase is combined with 10°C warming. The model seems to accurately portray the sensitivity of white spruce to warming-induced moisture limitation and recovery time between disturbances.

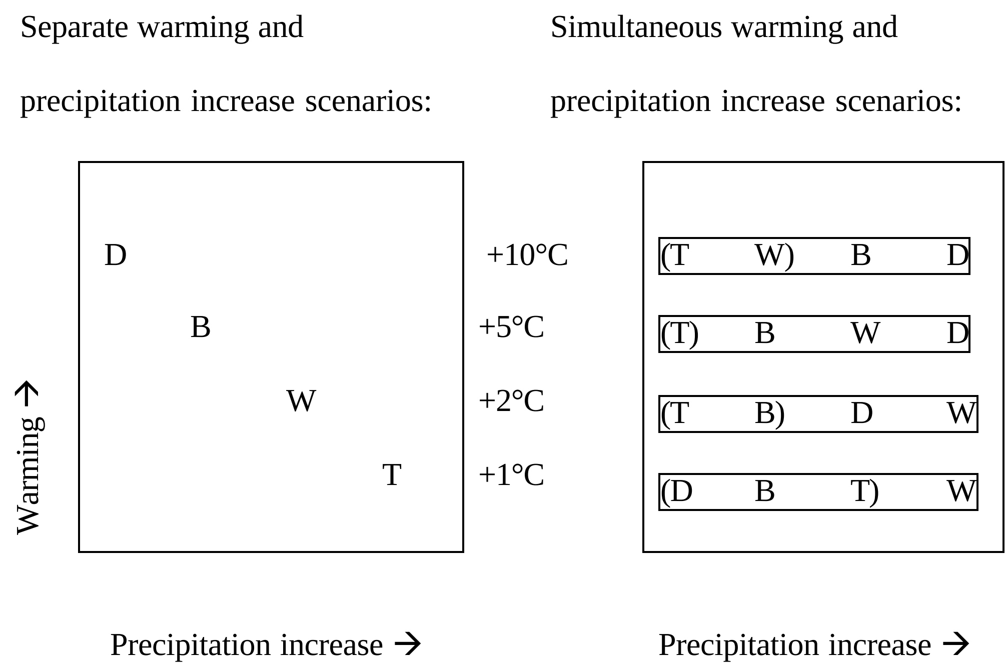
Deciduous forest currently accounts for only 1% of the simulated vegetation of Interior Alaska. This vegetation type expands under warming, precipitation decrease, and fire interval decrease. It responds up to five times more strongly to combinations of these change scenarios than to individual changes. Deciduous forest is one of the most dynamic vegetation types being able to expand to 12% of Interior Alaska under fire interval decrease with simultaneous 10°C warming. In the logistic regression simulations, deciduous forest increases its area under fire interval decrease with precipitation decrease, and precipitation decrease with warming. Simulations by Rupp *et al.* (2000)

show the same trends, where both warming and fire improve deciduous forest growth. Bonan *et al.* (1990) conclude that the biomass of trembling aspen and paper birch increase with warming, reaching maxima at 5°C and 60% precipitation increase. Deciduous forest is an early successional stage in areas outside active floodplains (Mann *et al.* 1995), which over time is replaced by either black or white spruce (Van Cleve *et al.* 1986, Viereck *et al.* 1986). Clearly, a decrease in recovery time between burns would improve the competitive ability of deciduous forest over spruce in the landscape.

The simulations with the logistic regression model under combined changes in growing season temperature, growing season precipitation and fire interval show that vegetation type responses to these factors are not linear. Vegetation types respond differently to simultaneous changes in two environmental parameters versus changes in only one environmental parameter indicating interactions between environmental variables. If separate warming and precipitation increase results are plotted together in a 2-dimensional graph, they display a clear diagonal pattern (Figure 4.13).

When precipitation and temperature changes are imposed on vegetation individually, the four major vegetation types in Interior Alaska align themselves along a different gradient than when the climate changes are imposed simultaneously (Figure 4.13). Deciduous forest responds well to warming and low precipitation under separate simulations. When precipitation and warming are coupled, however, deciduous forest expands most under high temperature with high precipitation. Black spruce only expanded its range if precipitation decreases or if precipitation increase is coupled with at least a 5°C warming. White spruce expands most under wetter conditions and could tolerate warmer temperatures as long as precipitation does not become limiting, as is the case once temperatures increased by 10°C.

Figure 4.13: Two-dimensional gradients for vegetation responses to warming and precipitation increase



vegetation types in parentheses decrease; B = black spruce forest, D = deciduous forest, T = tundra, and W = white spruce forest.

The interaction between two environmental change inputs can lead to landscapes that differ from the landscapes created when either scenario is imposed individually (Figure 4.9). On the other hand, warming by 10°C is a stronger driver for vegetation change than changes in either precipitation or fire interval in coupled change simulations.

Based upon the Hadley CM2 climate scenario, Interior Alaska in 2100 will consist of mostly black spruce forest with some deciduous forest, which does not include the effect of potential changes in fire regime. The logistic regression model is an equilibrium model that does not account for transitory changes as the vegetation adapts to the new climate, such as dispersal, establishment, and changes in soil conditions (temperature, moisture, nutrients) and permafrost. The model simulates potential vegetation which might be unrealistic as species assemblages could change under new climate conditions (Davis 1989, Kirilenko and Solomon 1998). A transient model for Alaska showed that it would take 150 years for the conversion of tundra to forest after 3°C instant warming and 80 years after 6°C warming (Starfield and Chapin 1996). A dynamic global vegetation model predicted a loss of 50% of all tundra north of 50°N by 2100 using the same Hadley CM2 climate scenario (White *et al.* 2000). This change in boreal forest vegetation composition can have far-reaching effects on climate through changes in albedo and other surface properties potentially leading to new feedbacks among vegetation, disturbance, and climate (Bonan *et al.* 1992, Chapin *et al.* 2000, Zhao *et al.* 2001).

In conclusion, the logistic regression model was capable of producing reasonable trends in vegetation type responses to climate change and compared well with other models, despite its simplicity. Interior Alaska is facing a gradual loss of alpine tundra and white spruce forest with an expansion in black spruce and deciduous forest. Precipitation will become a crucial variable in the impact of warming on boreal forest composition of the future. To improve vegetation change predictions, several environmental parameters should be altered simultaneously to allow for the effect of interactions among parameters on vegetation.

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Chapter 5 - Land cover estimates in Interior Alaska across classifications and resolutions

5.1 Abstract

Modeling the effects of climate change in Alaska at regional scales requires vegetation data sets that accurately identify vegetation types across the landscape. This study evaluated the compatibility and accuracy of currently existing classifications for Interior Alaska as well as the effect of scale on accuracy of land cover estimates. Four 1km-resolution based land cover classifications were compared with each other and with a 25m-resolution Thematic Mapper ™ image. Total overall agreements among vegetation classifications range from 36% to 96%. Agreements between the four 1km-resolution classifications and the TM image range from 40% to 65%. Kappa values are very low indicating that much of the agreement between different classifications can be attributed to random chance. The resolution of the vegetation classification affects the representation of vegetation types; the major vegetation types eliminate the smaller types with increasing coarseness. The land cover classifications developed at the state and continental scales do not accurately represent the vegetation at finer resolutions in Interior Alaska.

5.2 Introduction

There is concern about the response of the vast carbon pools stored in the circumpolar boreal forests to global warming (Serreze *et al.* 2000, Keyser *et al.* 2000, Hobbie *et al.* 2000). Most of the boreal forest in Alaska is concentrated in its interior, which extends over roughly 300,000km^2. Interior Alaska is already showing responses to climate change prompting a demand for modeling potential future land cover patterns (Keyser *et al.* 2000, Jorgensen *et al.* 2001). Remote sensing may be the only approach to creating regional scale land cover maps for this vast and relatively inaccessible area. During land cover classification and map development, inaccuracies can be introduced by satellite data quality, suitability of reference data, classification method, interpreter skills and performance, and resources (e.g. budget, staff, time) (Loveland *et al.* 1999). Ground truthing a classification can be very difficult, time consuming, and costly (Congalton 1988, Loveland *et al.* 1999). An alternative is the comparison of several classifications with each other, preferably using a relatively high-resolution classification as a reference such as Landsat scenes or air photos (Fleming 1988, Muchoney *et al.* 1999). However, this method can introduce new errors due to registration-noise (Gong *et al.* 1992) or misregistration (Singh 1989, Stow 1999, Verbyla and Boles 2000) which occurs when the two images are slightly offset. Another problem is misclassification due to heterogeneous landscapes with land cover patches smaller than the pixel size of the classification thereby resulting in mixed pixels (Steele *et al.* 1998) or conservative bias due to minimum mapping units (Verbyla and Hammond 1995). When minimum mapping units (MMU) are larger than classification pixel size, vegetation patches smaller than the

MMU are excluded from the classification leading to an incomplete representation of the actual land cover in the classification (Verbyla and Hammond 1995).

For the boreal forest region in Interior Alaska, there are currently two widely used land cover classifications available. One is a classification created from 1991-1992 AVHRR (Advanced Very High Resolution Radiometer) images by Fleming (1997). The other is based on 1992-1993 AVHRR images and was created by the USGS (Loveland *et al.* 1999). Both classifications are based on 1km pixel sizes and a multitude of vegetation types. The land cover of Interior Alaska alone, for example, consists of 23 types in the Fleming classification (1997) and 37 types in the USGS classification (Loveland *et al.* 1999). Dynamic vegetation modeling could require parameterization for each vegetation class in the model; however, it may be very difficult to determine parameters for so many different vegetation classes. Rupp (unpublished data) therefore developed an approach to reduce Fleming’s vegetation classes to the four major types found in Interior Alaska: tundra, deciduous forest, black spruce forest, and white spruce forest. Rupp's algorithm is based on generally accepted field information about the distribution of white versus black spruce communities in Interior Alaska (Foote 1983, Viereck 1983, Van Cleve *et al.* 1983, Van Cleve *et al.* 1986, Dyrness *et al.* 1986): Black spruce communities are located on northern aspects and flat slopes, while white spruce is found on southern aspects and at the timberline. The Rupp vegetation classification was further processed by Copass and Silapaswan (unpublished data) in the context of the Western Arctic Linkage Experiment (WALE) project at the University of Alaska Fairbanks. This additional processing attempted to improve the classification and expand it into Canada by reclassifying a similar Canadian classification (Cihlar *et al.* 1996, Cihlar and Beaubien 1998).

Interior Alaska consists of rather homogeneous forest compared to other areas; however, 1km pixel size might be too coarse to represent all the variability found on the landscape. This lack of detail might average out over a larger landscape, or it could lead to misrepresentations of vegetation types in the classification.

The questions that are addressed in this study are:

1. How do the land cover classifications differ in Interior Alaska?
2. Which classification is most accurate when compared with a higher resolution TM image?
3. How does pixel size affect the representation of vegetation types in the classification?

5.3 Methods

Five vegetation classifications were compared: the USGS Land Cover Characterization (Loveland *et al.* 1999), Fleming's Vegetation of Alaska (Fleming 1997), Rupp's adaptation of Fleming's classification (unpublished data), the WALE classification (named after the Western Arctic Linkage Experiment project it was created for) (unpublished data), and a Landsat Thematic Mapper (TM) classification (Verbyla and Boles 2000). The first four classifications have $1km^2$ pixel sizes and extend over all of Alaska, while the TM scene consists of 25m pixel sizes and only includes a $8,570km^2$ area south of Fairbanks, which is located roughly in the center of Interior Alaska (Figure

5.1). The TM classification is used as a reference for validating the other four classifications.

Figure 5.1: Location of TM Scene in Alaska

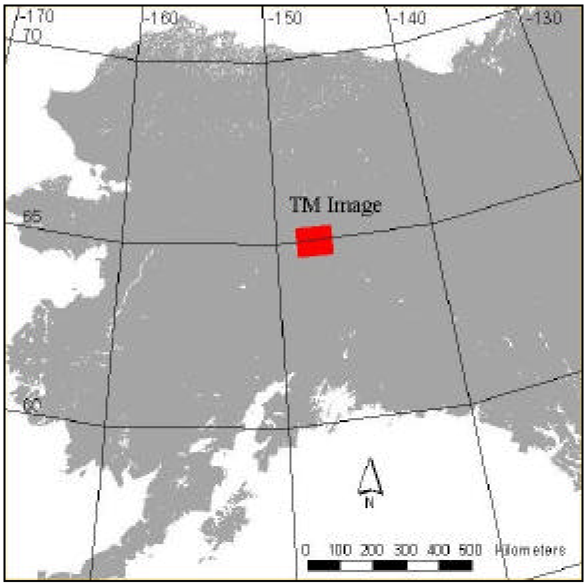
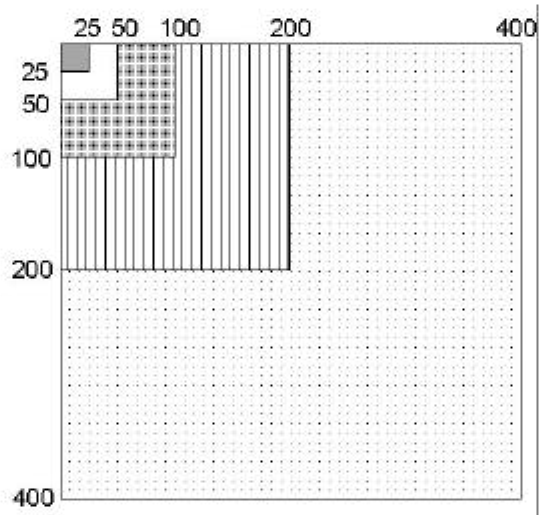


Figure 5.2: Nested Blocks



Since each vegetation classification has very different classes, a direct comparison was impossible. To allow comparisons among the data sets, all vegetation classifications were reduced to only three vegetation types based on their legend descriptions: tundra/shrubs, deciduous/mixed forest, and spruce forest (Appendix 5.1). All areas classified as ice, water, rock, or burn, etc. were categorized as 'no data.' To match the other data sets, the 25m-resolution TM classification was aggregated (see next paragraph on aggregation method) to 1km^2 pixel size. Comparisons were then performed among all five classifications within the same area south of Fairbanks that is covered by the TM image. An error matrix or contingency table was created for calculation of overall accuracy - using the TM image as reference data - and the kappa or k-hat statistic (Congalton *et al*. 1983, Erratum Photogrammetric Engineering and Remote Sensing 50(10):1477).

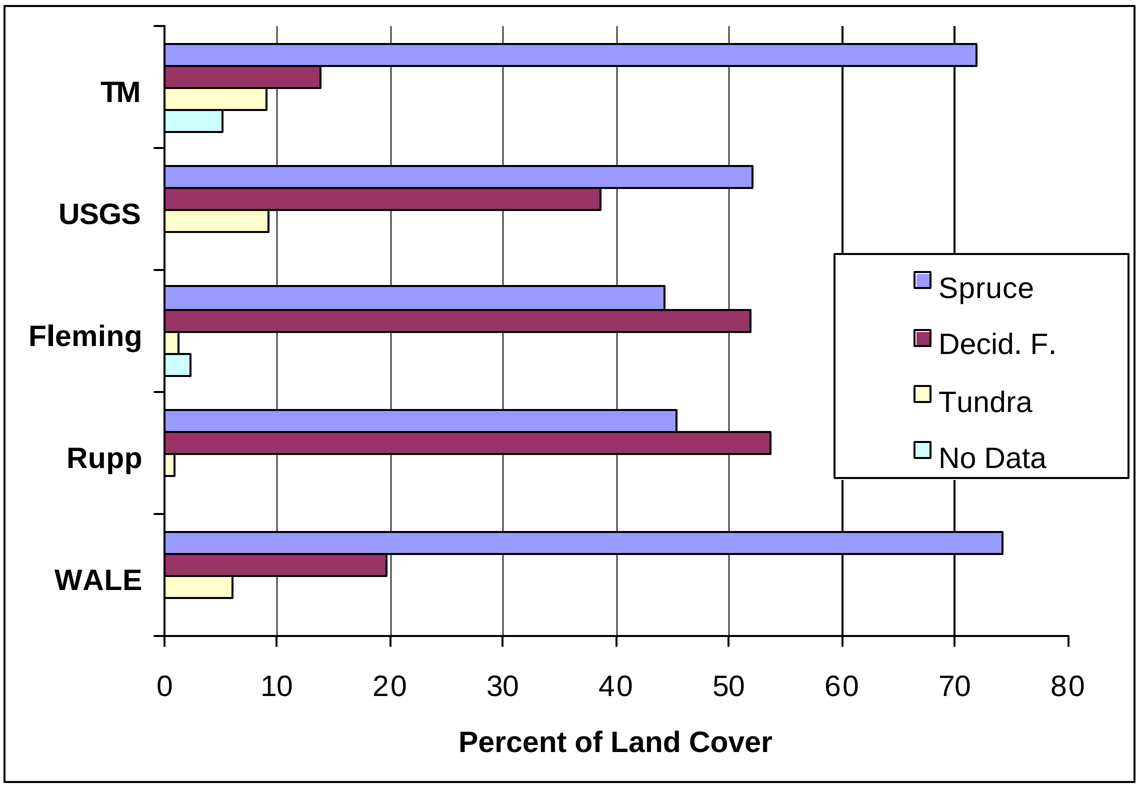
To see how much of the agreement between classifications is explained by simple random chance, I randomized the Verbyla vegetation grid so that the same mean landscape distribution of vegetation types is found but the location of vegetation pixels is random. This random 'reference' classification was then compared with the AVHRR-based classifications.

To determine if pixel size had an effect on how vegetation types were represented in the classification, the TM classification was additionally aggregated to 50m x 50m, 100m x 100m, 200m x 200m, 400m x 400m, and 800m x 800m pixel sizes. Aggregation was performed by creating nested 'blocks' of the desired coarser cell sizes and then assigning the vegetation type with the highest frequency to this new block (Figure 5.2). If two or more vegetation types had the same number of pixels, the new cell was dropped from the analysis as no clear dominance could be established. This aggregation was performed on both the original 17 land cover classes and the grouped classes.

5.4 Results

Vegetation type distribution across the landscape varies largely among classifications (Figure 5.3). However, a chi-square test at a = 0.95 test yielded no significant difference among the four AVHRR-based classifications and the TM classification, probably due to the very large variability of pixels in each vegetation type. The TM, USGS, and WALE classifications are dominated by spruce forest, while the Fleming and Rupp classifications are dominated by deciduous forest.

Figure 5.3: Vegetation distribution across classifications (in percent)



Overall similarity between the AVHHR-based classifications ranges from 96% (Fleming versus Rupp) to 36% (Fleming versus WALE) (Table 5.1). The Fleming and Rupp classifications have >90% agreement regarding the position of deciduous forest and spruce forest pixels. On the other hand, most of the tundra in Fleming is classified as deciduous forest in Rupp, while most of the tundra in Rupp is classified as spruce forest in Fleming. The Fleming classification is in good agreement with the other three

Table 5.1: Agreement among classifications (in km^2)

	Fleming			
USGS	**Tun**	**Dec**	**Spr**	**%**
Tun	21	113	669	3
Dec	37	2574	730	76
Spr	60	1851	2474	54
%	18	57	64	**59**

	Rupp			
USGS	**Tun**	**Dec**	**Spr**	**%**
Tun	54	124	632	7
Dec	-	2628	749	78
Spr	29	1935	2586	57
%	65	56	65	**60**

	WALE			
USGS	**Tun**	**Dec**	**Spr**	**%**
Tun	213	251	346	26
Dec	22	440	2915	13
Spr	294	1028	3225	71
%	40	26	50	**44**

	Fleming			
WALE	**Tun**	**Dec**	**Spr**	**%**
Tun	13	97	419	2
Dec	66	574	950	33
Spr	39	3863	2504	39
%	11	13	65	**36**

	Rupp			
WALE	**Tun**	**Dec**	**Spr**	**%**
Tun	79	97	353	15
Dec	-	738	981	43
Spr	4	3848	2633	41
%	95	16	66	**40**

	Fleming			
Rupp	**Tun**	**Dec**	**Spr**	**%**
Tun	16	-	67	19
Dec	102	4377	-	93
Spr	-	161	3806	96
%	14	96	98	**96**

Total accuracy (in bold) = (Sum of the diagonal values) / (total number of pixels)

% = Percent agreement between classifications

Tun = Tundra/Shrub

Dec = Deciduous/Mixed Forest

Spr = Spruce Forest

AVHRR-derived classifications regarding the position of spruce forest. It also has good agreement regarding deciduous forest with the USGS and Rupp classifications. The USGS classification has good agreement with the Rupp classification regarding tundra and with the WALE classification regarding spruce. The area classified as tundra in the WALE classification contains 95% of the area classified as tundra by Rupp and 66% of the area classified as spruce forest by Rupp.

When the 1km-based classifications are referenced with the TM image, overall accuracy ranges from 65% (WALE) to 40% (Fleming) (Table 5.2). The classifications are best in determining the location of spruce forest, followed by tundra. Seventy-two percent of the TM image is classified as spruce forest, which is a much larger area than in the other classifications (except the WALE classification). As a result, a large portion of the pixels assigned to mostly deciduous forest and some tundra types in the 1km classifications potentially should have been identified as spruce forest. The USGS classification identifies 44% of the tundra correctly, which is much better than any of the other classifications. Since the Fleming and Rupp classifications contain only very little tundra area, they identified less than 5% of the tundra in the TM classification. The largest number of correct spruce pixels was designated in the WALE classification (79%), the least in the Fleming classification (41%). The kappa values (Cohen 1960, Congalton 1991) are: USGS 0.10, Fleming –0.003, Rupp –0.03, and WALE 0.12 indicating 'poor' (for values <0) and 'slight' (for values between 0 and 0.2) strength of agreement (Landis and Koch 1977).

Comparing the AVHRR-based classifications with the randomized TM classifications shows that there is much random agreement (Table 5.3). This explains why the kappa values were low overall.

As TM pixel size increases from 25m to 800m, the landscape distribution of spruce forest increases from 54% to 67%, thereby replacing deciduous forest and shrub tundra, which decrease from 20% to 13% and 16% to 11%, respectively (Figure 5.4). The resulting landscapes at all aggregated pixel sizes are significantly different from the original 25m based on chi-square testing at a = 0.95 for both the original 17 land cover classes and the aggregated land cover classes.

Table 5.2: Error matrix for classifications

Reference Data (TM)

USGS	**Tundra**	**Deciduous**	**Spruce**	**% correct**[1]
Tundra	346	34	327	43
Decid	124	590	2595	17
Spruce	320	593	3357	74
% correct[2]	44	48	53	**52**[3]

Fleming	**Tundra**	**Deciduous**	**Spruce**	**% correct**[1]
Tundra	23	22	22	19
Mixed	169	677	3601	15
Spruce	585	506	2597	67

% correct[2]	3	56	41	**40**[3]

Rupp	**Tundra**	**Deciduous**	**Spruce**	**% correct[1]**
Tundra	31		46	37
Decid	172	700	3596	15
Spruce	587	517	2637	66
% correct[2]	4	58	42	**41**[3]

WALE	**Tundra**	**Deciduous**	**Spruce**	**% correct[1]**
Tundra	127	8	369	24
Decid	213	349	970	20
Spruce	450	860	4936	76
% correct[2]	16	29	79	**65**[3]

[1] This column expresses user accuracy or error of commission.

[2] This row expresses producer accuracy or error of omission.

[3] The total accuracy is calculated as the sum of the diagonal values over the total number of pixels.

Table 5.3: Comparison with random number based image*

USGS	**Tundra**	**Deciduous**	**Spruce**	**% correct**
Tundra	129	87	548	16

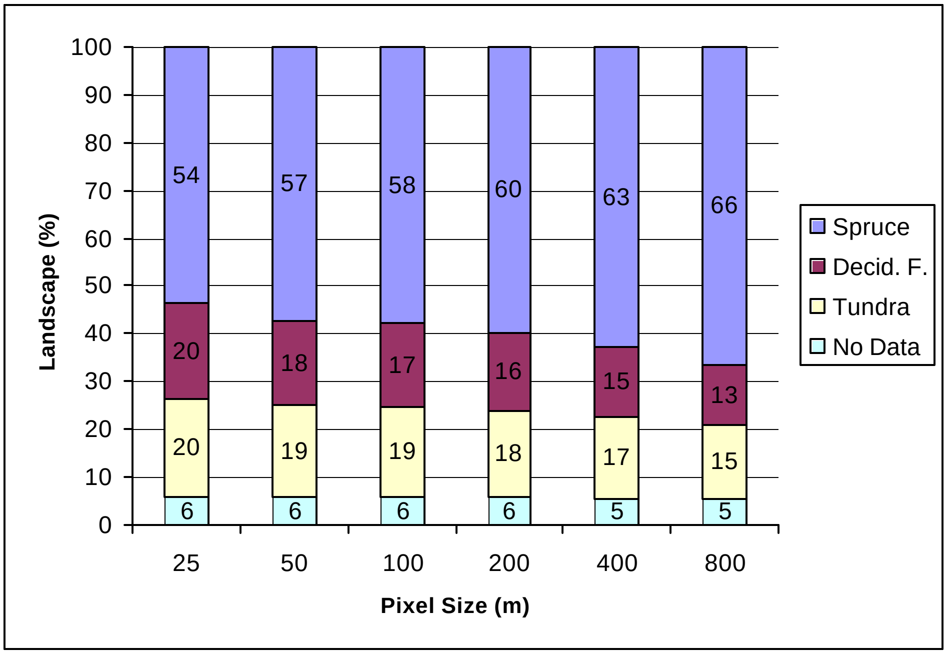
Deciduous	458	430	2298	13
Spruce	674	567	3070	67
% correct	10	40	52	**44**

Fleming	**Tundra**	**Deciduous**	**Spruce**	**% correct**
Tundra	17	17	76	14
Deciduous	637	548	3106	12
Spruce	570	484	2612	67
% correct	1	51	44	**39**

Rupp	**Tundra**	**Deciduous**	**Spruce**	**% correct**
Tundra	11	8	61	13
Deciduous	663	576	3181	12
Spruce	587	500	2673	67
% correct	1	53	45	**39**

WALE	**Tundra**	**Deciduous**	**Spruce**	**% correct**
Tundra	96	59	349	18
Deciduous	261	214	1139	12
Spruce	904	810	4426	68
% correct	8	20	75	**57**

Figure 5.4: Landscape distribution across scales



5.5 Discussion

The distribution of the three aggregated vegetation types varied largely among classifications. The TM-image and the WALE classification produced landscapes that were largely dominated by spruce forest, while the other classifications showed a more even distribution of spruce and deciduous forest (Figure 5.3). The Rupp and Fleming classifications contained almost no tundra.

There was large disagreement among the classifications regarding the position of tundra. Most of the area labeled as tundra in the USGS classification was categorized as spruce forest in the other three AVHRR-based classifications (Table 5.1). Most of the area classified as tundra by Fleming was classified as spruce forest in the USGS classification and deciduous forest in the WALE and Rupp classifications. Loveland (1999b) noted that when the USGS classification was developed, one of the major problems was the differentiation between open forest and woodland. Aggregation of these types based on legend names introduces additional inaccuracies because the same open woodland type forest could be called 'forest' in one classification and 'shrub land or tundra' in another. The best agreement between classifications was reached for spruce forest which was by far the most dominant vegetation type. There was some overlap between deciduous forest and spruce forest which might be an artifact of the aggregation that included mixed forest with deciduous forest. It was problematic that each land cover classification has an unmanageably large number of land cover types and that the land cover types are very different in each classification thus making direct comparison extremely difficult.

Overall accuracy of all four AVHRR-based classifications was low. Since the TM image has a much finer resolution, this classification is assumed to be more accurate than the coarse classifications. It is common practice to verify coarse satellite data (1km resolution) with fine scale satellite data or aerial photographs and this approach was used during development of the USGS global land cover characterization (Muchoney *et al.* 1999). I therefore assumed that the TM classification was the closest approximation of the true landscape in lieu of other available data sets when compared with the four AVHRR-based classifications. The USGS classification identified the largest amount of tundra correctly, while the WALE classification identified the largest amount of spruce forest correctly. Both the WALE and Fleming classifications assigned half of the deciduous forest pixels accurately. Based on overall accuracy values and kappa (k-hat) statistics, the WALE classification was most accurate; Fleming's classification had the lowest overall accuracy. Further processing and aggregation of the Fleming classification into the Rupp and WALE data sets improved overall classification accuracy. One has to keep in mind that aggregating vegetation classes introduces additional error, which might skew the comparison of land cover classifications with aggregated classes. The results therefore do not reflect the absolute accuracy between two classifications but should only be viewed as relative comparisons.

Another problem is the fact that there are three vegetation types, one of which (spruce) overwhelmingly dominates the landscape accounting for more than 70% of the vegetation at 1km resolution. Thus, simple random chance alone accounts for a large part of the agreement observed among the classifications (Table 5.3). In fact 44% of the overall accuracy of the USGS classification can be attributed to random chance, which is reflected in the very low kappa values observed. This very low agreement among the classifications can be attributed to several causes: misregistration, temporal differences, and differences in area of classification development. Misregistration occurs when the images are not lined up perfectly but are instead offset by one or more pixels in one or two directions. The pixels in the five classifications used here are not perfectly aligned as the classifications were developed independently of each other. The TM classification was based on one image representing one day during the growing season compared to the USGS and Fleming classifications which are based on changing vegetation signals throughout an entire year. Finally, the Fleming classifications was developed over the entire state of Alaska, while the USGS classification is global. On a statewide level, Alaskan vegetation can be described as coastal tundra in the West and North, coastal forest in the South and Southeast, and some type of spruce forest interspersed with deciduous forest in the topographically complex Interior (Viereck *et al.* 1992). The regional to continental scale classifications were developed to reflect these large patterns and cannot be expected to accurately represent the complex vegetation patterns in the smaller but more complex region of Interior Alaska. Additionally, each remotely derived classifications has its own inaccuracies. Based on selected verification sites, the USGS classification achieved an overall accuracy of 63% for North America but only 45% accuracy for the North American boreal and arctic zones (Scepan 1999). The Fleming, Rupp, and WALE classifications were also never thoroughly ground truthed. With such low overall accuracy, does the comparison among AVHRR-based classifications even mean anything? I want to emphasize that the comparison and accuracy values in this analysis should serve only as a qualitative assessment. Despite their obvious flaws, the vegetation classifications discussed here are the best available at this time to study climate change and vegetation patterns in Alaska and the scientific community is aware that these data are not 100% accurate (Townshend 1992, Sellers *et al.* 1995). As Loveland (1999b) states: "The fundamental problem… is more likely attributed to the difficulty of using coarse resolution satellite data to map relatively fine-scaled land-cover patterns that comprise cover types with overlapping spectral signatures."

This statement is confirmed with the resolution analysis. Pixel size had a significant effect on vegetation distribution, indicating that vegetation patterns in Interior Alaska occur at scales finer than 1km. The dominant vegetation type increased in dominance as pixel size increased, thereby 'encroaching' on intermediate vegetation classes. Only the small 'no data' class remained relatively constant. Markon and Peterson

(2002) also found that local vegetation types do not scale linearly to larger regions. The bottom line for ecological modeling of global climate change in Alaskan boreal forest is that there is a need for accurate land cover classifications at finer resolutions and with fewer, more consistent land cover classes.

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Appendix 5.1: Aggregation Tables for Classifications

TM Classification (Verbyla and Boles 2000)

Vegetation Type	Aggregate	Area (km^2)
Alpine Tundra	Tundra	100
Alpine Tundra	Tundra	9
Shrubland	Tundra	586
Shrubland	Tundra	95
Broadleaf Forest	Deciduous Forest	521
Broadleaf Forest	Deciduous Forest	137
Broadleaf Poles	Deciduous Forest	147
Broadleaf Wetland	Deciduous Forest	412
Spruce Forest	Spruce	5973
Spruce Woodland	Spruce	306
Recent Burn	No Data	22
Clear Water	No Data	24
Turbid Water	No Data	88
Urban/Gravel	No Data	90
Gravel/Smoke	No Data	99
Clouds	No Data	93
Cloud Shadows	No Data	36

USGS Classification (Loveland 1999)

Vegetation Type	**Aggregate**	**Area (km^2)**
Wet herbaceous meadows	Tundra	1
Herbaceous Alpine Tundra	Tundra	1
Herbaceous Alpine Tundra with low/dwarf shrubs	Tundra	12
Woody arctic tundra	Tundra	640
Tall/low Shrubs, tundra, spruce	Tundra	3
Tall shrubs (willow, birch, alder) and wet herbac. meadows	Tundra	61
Shrub fens and bogs	Tundra	92
Deciduous forest and tall shrubs (willow, birch, alder)	Decid. For.	296
Open mixed forest (aspen, birch, white spruce, black spruce)	Decid. For.	248
Mixed forest (aspen, birch, balsam poplar, bl. & wh. spruce)	Decid. For.	2829
Mixed forest (black and white spruce, aspen, birch)	Decid. For.	4
White, black spruce forest	Spruce	740
Spruce forest	Spruce	1178
Evergreen needleleaf forest (balsam fir, bl. spruce, wh. spr.)	Spruce	11
Evergreen needleleaf forest and woodland (bl. & wh. spr.)	Spruce	1
Spruce woodlands and shrub bogs	Spruce	267
Open spruce forest with tall shrubs (willow, birch, alder)	Spruce	1876
Black spruce, tamarack, lichen woodland	Spruce	446
Spruce woodland with low/tall shrubs	Spruce	32

Fleming (1997)

Vegetation Type	**Aggregate**	**Area (km^2)**
Dwarf Shrub Tundra	Tundra	10
Tall Shrub	Tundra	108
Closed Mixed Forest	Deciduous Forest	37
Spruce & Broadleaf Forest	Deciduous Forest	4340
Open Spruce & Closed Mixed Forest Mosaic	Deciduous Forest	161
Spruce Woodland/Shrub	Spruce	748
Open Spruce Forest/Shrub/Bog Mosaic	Spruce	1805
Open & Closed Spruce Forest	Spruce	1229
Close Spruce & Hemlock Forest	Spruce	91
Water	No Data	1
1991 Fires	No Data	14
1990 Fires & Gravel Bars	No Data	194

Rupp (unpublished data)

Type	**Aggregate**	**Area (km^2)**
Tundra	Tundra	79
Deciduous Forest	Deciduous Forest	4600
Black Spruce	Spruce	2816
White Spruce	Spruce	1075

WALE (unpublished data)

Type	**Aggregate**	**Area (km^2)**
Tundra	Tundra	529
Deciduous Forest	Deciduous Forest	1719
Black Spruce	Spruce	4290
White Spruce	Spruce	2196
Snow/Ice	No Data	4

Chapter 6 - Conclusions

Despite the coarseness of a vegetation classification at 1km scale, patterns regarding vegetation and topography reflected those described in field studies at the local scale for Interior Alaska. The four major vegetation classes from the USGS classification arrange themselves along gradients of elevation and to some degree aspect. Fire incidence peaks at 100-200m elevation, S, NW, and SW aspects, and decreases with increasing elevation or slope; vegetation classes containing black spruce burn more than other types. On a regional scale it seems that topography dictates vegetation type distribution, which in turn influences fire behavior. Vegetation succession after fire disturbance was not clear due to the coarseness of the vegetation classification and the short time period available on record.

A logistic regression model of vegetation patterns in Interior Alaska was simple in nature but capable of predicting current vegetation in Interior Alaska and Western Canada with reasonable accuracy. The most important driver between tundra versus forest is elevation indicating that Interior Alaska contains only alpine tundra. Deciduous forest and spruce forest are driven by fire confirming that they can be found at different times during succession and are characterized by very different fire regimes. Black and white spruce are driven by their different topographic locations and the time since last fire. The logistic regression model was also capable of distinguishing bogs from all other vegetation types.

Based on the Hadley CM2 climate prediction for 2100, Interior Alaska will shift towards more black spruce with some deciduous forest, while the extent of alpine tundra will be vastly reduced. When temperature, precipitation, and fire interval were manipulated, deciduous versus spruce forest was driven by the successional sequence of these vegetation types, which is represented by time since the last fire. Warming resulted in increases in black spruce and deciduous forest, while precipitation increase led to increases in tundra. White spruce expanded as long as warming did not exceed 2°C at which point moisture seemed to become limiting. When compared with fire interval or precipitation changes, 10°C warming was the stronger driver for vegetation change in Interior Alaska. The logistic regression model produced reasonable results when compared to other models.

There is poor agreement among currently available vegetation classifications for Interior Alaska. Additionally, too many vegetation classes and unclear naming conventions make it difficult to use these data sets for modeling, to compare different classifications, and to assess their accuracy. A major portion of the agreement between different classifications can be attributed to random chance alone. On the other hand, state and continental scale classifications are not very accurate in Interior Alaska. Overall, the WALE classification seemed to have the highest accuracy when compared with a finer scale TM image.

The vegetation classifications tested were affected by scale indicating that vegetation patterns in Interior Alaska occur at a finer scale than 1km. The bottom line for ecological modeling of global climate change in Alaskan boreal forest is that there is a need for accurate land cover classifications at finer resolutions and with fewer, more consistent land cover classes.