GREENING OF RECENTLY DEGLACIATED LANDS ON

THE KENAI PENINSULA

A Thesis

by -

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ABSTRACT

Poleward vegetation expansion has affected Alaska for decades and due to recently increased rates of warming, the expansion will accelerate. Glacier recession in the region has exposed land that was previously ice covered. Within a few years, initial succession begins to take place over the newly exposed land. Changes in land cover of recently deglaciated areas are affected by surface-air interactions, temperature gradients, and ecosystem development. Using data gathered from Landsat 5, 7 and 8 and previous extents of select, retreating glaciers within the Kenai Peninsula, this research examines the relationship between glaciation rates and greening. Combining historic glacier extents with Landsat images gathered from Google's Earth Engine platform I was able to identify annual summer changes in NDVI for locations deglaciated by 1995, 2005 and 2015. The glaciers were selected based on location and average retreat rate measured between 1950 and 2005. Dinglestadt, Chernof, Petrof, Yalik, Killey, Kachemak, Lowell, and Exit are all land or lake terminating glaciers within the Kenai Peninsula. The faster retreating glaciers exhibited higher mean and maximum NDVI in their longest deglaciated regions while slower retreating glaciers showed a near constant, lower NDVI throughout the recently deglaciated foreground.

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Contributors

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NOMENCLATURE

asl	above sea level
AVHRR	Advanced Very High Resolution Radiometer
GEE	Google Earth Engine
GLIMS	Global Land Ice Measurements from Space
GYGC	Grewingk-Yalik Glacier Complex
HI	Harding Icefield
IPCC	Intergovernmental Panel on Climate Change
KEFJ	Kenai Fjords National Park
LST	Land Surface Temperature
MODIS	Moderate Resolution Imaging Spectroradiometer
NDSI	Normalized Differential Snow Index
NDVI	Normalized Differential Vegetation Index
SAVI	Soil Adjusted Vegetation Index
USGS	United States Geological Survey

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Introduction

Cryosphere is the term designated to all ice-covered areas of the earth, this list includes but is not limited to sea ice, snow-covered grounds, ice sheets, and glaciers. Global climate change is a threat that reaches all portions of the cryosphere. Warming across the planet has led to increased melt and poleward vegetation expansion as more energy is introduced into the high latitude systems (Jeong et al. 2012). The poleward growth in-turn has made it more difficult for glaciers and ice caps to grow during the winter months.

Through their annual variability, glaciers provide a special view into the nature of climate change. No two glaciers are the same. Each possess varying mass, densities, and recession rates even under similar weather and climate regimes. The fifth assessment report from the Intergovernmental Panel on Climate Change (IPCC) estimates the world's glaciers hold enough water to raise the sea level roughly 412 millimeters (Vaughan et al. 2013). This is enough to threaten major coastal cities. When glaciers melt, they carve valleys in the land they previously inhabited. Due to decreased ice coverage, the exposed darker soil or silt absorb more solar radiation than the ice they replaced (Hodson et al. 2008). Over months and years, the energy from this small heat trap radiates out and melts adjacent permafrost opening a path to vegetative expansion.

The causes and results of poleward vegetation movement have been well researched. A key concern is the feedback loop that can transform a region of barren land into a forest within a century or two (Chapin and Starfield 1997). This positive feedback loop is present in recently deglaciated landscapes. Starting initially with exposed soil and higher energy absorption due to lower albedo a deeper active layer soon follows. The pioneering vegetation begins to grow in this newly exposed soil and absorbs even more energy into the region leading to further glacial recession and more exposed soil. Global climate change will hasten this process. Although this feedback loop and the large role of temperature is known there is not enough understanding on what effects the vegetative expansion (Chapin et al. 2005).

The Kenai Peninsula is located just south of Anchorage in south central coastal Alaska. The summers along the Kenai Peninsula's exterior experience lush vegetation and relative warmth. Ice masses here are receding at higher rates than previously witnessed due to regional warming from the Alaskan Coastal Current and the previously mentioned feedback loop generated by the surrounding vegetation (Stabeno et al. 2016). The Harding Icefield (HI) and the Grewingk-Yalik Glacier Complex (GYGC) are both on the peninsula but experience slightly different temperatures due to the GYGC's more southern and coastal position. Regional warming and lower albedo is leading to more energy within the peninsula.

Following glacier recession, barren soil and rock are left behind. This deglaciated land begins to be colonized by moss, lichen, then shrubs and eventually trees. The time from initial soil exposure to moss and lichen cover varies between locations, soil type, snow/ice presence, and land surface temperature (Chapin et al. 1996; Tape et al. 2006). To measure these changes my research measured the Normalized Difference Vegetation Index

(NDVI) from eight glaciers on the HI and GYGC between 1991 and 2016. The purpose was to identify if higher glacial retreat rates have an effect on neighboring vegetation succession and growth rates. In the future, these findings may be added to regional cryospheric or vegetative change models to account for influences the two may have on one another and to reduce the likelihood of unexpected surprises regarding the strength of changes in high-latitude summer warming.

An increase in Arctic vegetation will have lasting effects in Earth-atmosphere interactions, regional climate, evapotranspiration rates, soil composition, albedo, and energy fluxes. Ecosystem changes also result in changing species interactions as vegetation attracts herbivores as well as decomposers who consume deceased animals and foliage (Blok et al. 2011; Myers-Smith et al. 2011). The introduction of vegetation into deglaciated areas changes an entire ecosystem.

Using NDVI and other remote sensing indices, vegetative succession can be measured through a time series analysis. By monitoring vegetation change in recently exposed foregrounds of glaciers receding at various rates, the importance glacial melt rate has on the regional portion of the feedback loop can be investigated. Traditionally, Arctic greening has been monitored using Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) (Jia et al. 2009; Myneni et al. 1997). Between the two satellites, a maximum spatial resolution of 250 meters is possible. In this project, images from Landsat 5, 7, and 8 enable these processes to be investigated at spatial resolutions of 30 meters. This higher resolution enables a more precise analysis than previous researchers have utilized. Here, I used the higher resolution images to measure glacial retreat and accompanying vegetation change and land surface temperature over a 25-year span from 1991 to 2016. This could not have been done as accurately using either AVHRR or MODIS.

The focus of this research is how vegetative succession in recently deglaciated areas relate to glacier retreat rates in the Kenai Peninsula and if it is possible to identify primary vegetative succession in deglaciated lands using current NASA Earth Observing satellites. This research's specific hypothesis is that vegetative succession in the foreground of a glacier follows a temporal pattern that is directly related to the rate of retreat and can be identified using NDVI collected from Landsat 5, 7, and 8. Land surface temperature, snow/ice presence, and elevation in the foreground may also have an effect, although these effects are secondary to the recession rate.

Study Area

According to recent estimates, glacier melt is responsible for roughly 8.4 centimeters of sea-level rise between 1800 and 2005. This means that between 35 and 50 percent of sea level rise since 1800 is due to glacial melt (Leclercq et al. 2011). With 87,100 square kilometers of glacier coverage, the Alaskan region has the fifth most ice-covered land of the 19 glacial regions. Alaska's glacial coverage represents 11.9% of the total coverage on Earth and 17.2% excluding Antarctica and Greenland (Gardner et al. 2013).

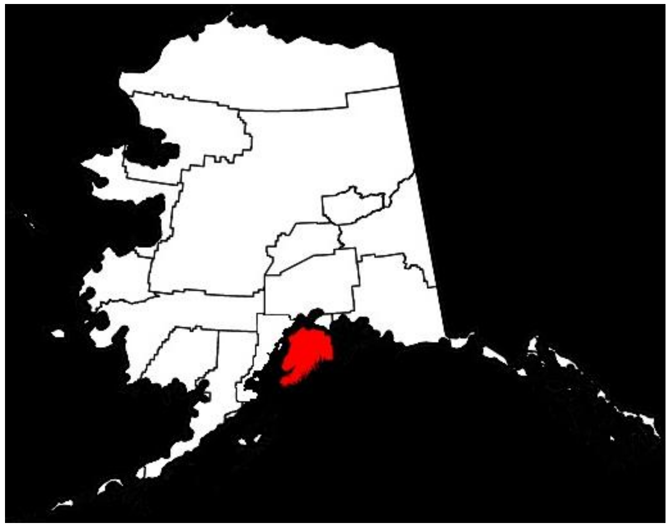


Figure 1: State of Alaska with the Kenai Peninsula highlighted (Adapted from David Benbennick and Wikimedia Commons)

The Kenai Peninsula in located in south central Alaska immediately south of Anchorage (See Figure 01). It is home to Chugach National Forest, Kenai Fjords National Park, and Kachemak Bay State Park. These three forested, protected areas are separated from the marshy, northern portion of the peninsula by various icefields. The Sargent and Harding Icefields as well as the Grewingk-Yalik Glacier Complex span the area along the center of the peninsula. This research focuses on eight select glaciers near the center of Kenai Peninsula that flow from HI and GYGC (See Figure 02 & Table 01). All data found in table 01 was reprinted from Giffen et al. 2014. The glaciers were deliberately selected because of previous studies in the area and that these glaciers well represent the non-tidewater glaciers in the area (Arendt et al 2002; Hall et al. 2005; VanLooy et al. 2006). The glaciers were separated into two groups: fast and slow retreating. The faster retreating glaciers, those classified as averaging more than 30 meters or more of linear retreat per year between 1950 and 1985, are expected to have an earlier vegetative response in the foreground than their slower retreating counterparts.

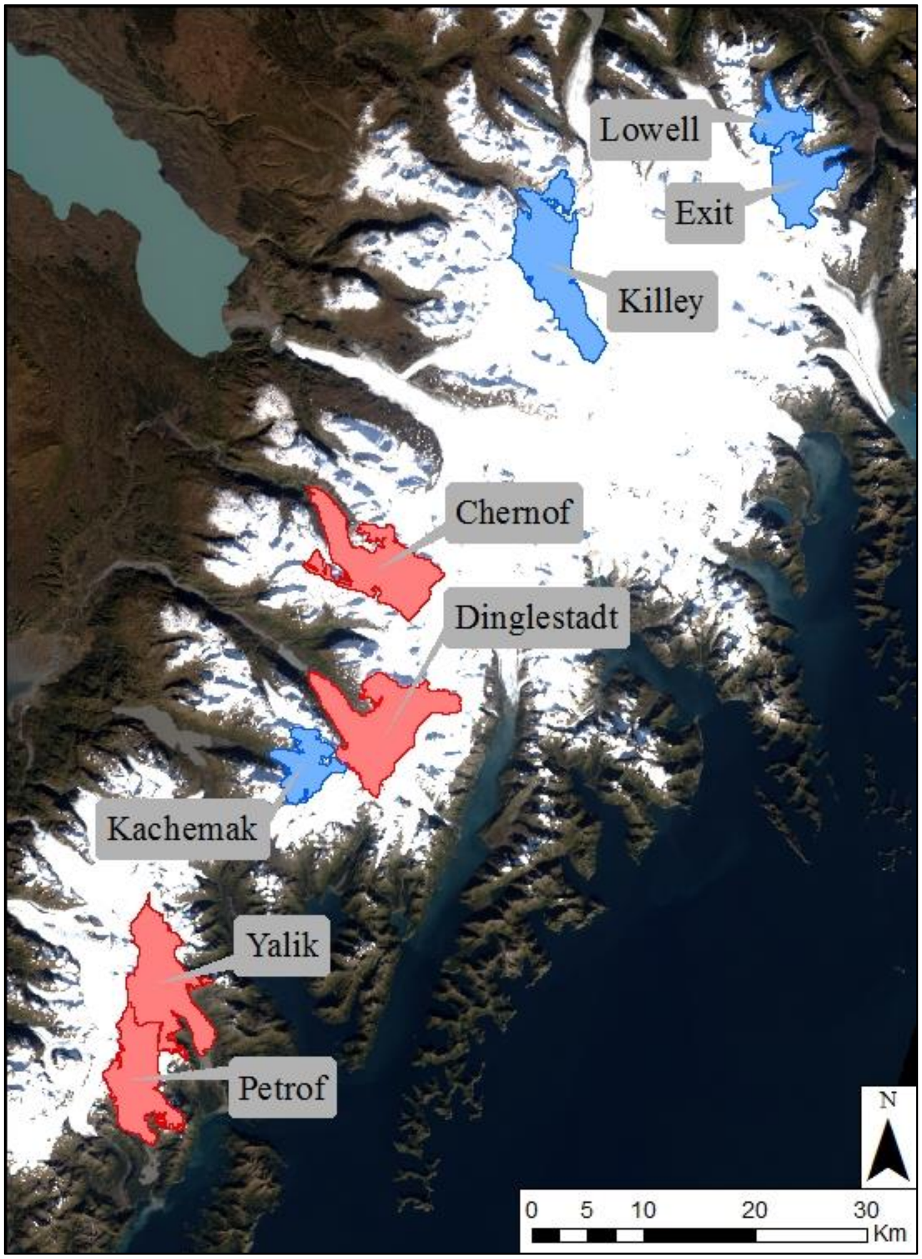


Figure 2: Map of glaciers.
Faster retreating glacier (blue) Slower retreating glacier (red)
(Base image adapted from Alaska Geospatial Council 2017)

Table 1: General Glacier Information.
Reprinted from Giffen et al. 2014

	Glacier Name	Avg. Annual Retreat from 1950 – 1985 (m/yr)	Total change from 1950 – 1985 (m)	Inland or Coastal	Land or Lake Terminating
Fast Retreating Glaciers	**Dinglestadt**	81	-2835	Inland	Lake
	Chernof	39	-1365	Inland	Land
	Petrof	36	-1260	Coastal	Land
	Yalik	30	-1050	Coastal	Land/Lake
Slow Retreating Glaciers	**Kachemak**	23	-805	Inland	Land
	Killey	23	-805	Inland	Land
	Lowell	21	-735	Inland	Land
	Exit	14	-490	Inland	Land

The Alaskan Center for Conservation Science through the University of Alaska Anchorage has produced vegetation maps of Alaska using land cover maps developed over the past 31 years. These maps contain both level III and level IV scales attributed to the Alaska Vegetation Classifications (ACCS 2016). This study uses the level IV classifications (See Figure 03). A multi-resource inventory was taken of the vegetation in south-central Alaska between 1978 and 1980. The south-central Alaskan region contains the Kenai Peninsula, Prince William Sound, Cook Inlet, and Kodiak Island. There were 19 forest types, 7 herbaceous types, and 3 shrub types identified in this region (Viereck et al 1992). Vegetation near HI and GYGC include Alder, Willow, and other Needle leaf tree species such as Black Cottonwood (*Populus trichocarpa*), Stika Spruce (*Picea sitchensis*), and White Spruce (*Picea glauca*). Shrub and grass types identified include resin birch (*Betula glandulosa*) and sedge-grass (ACCS 2016; Mead 1985).

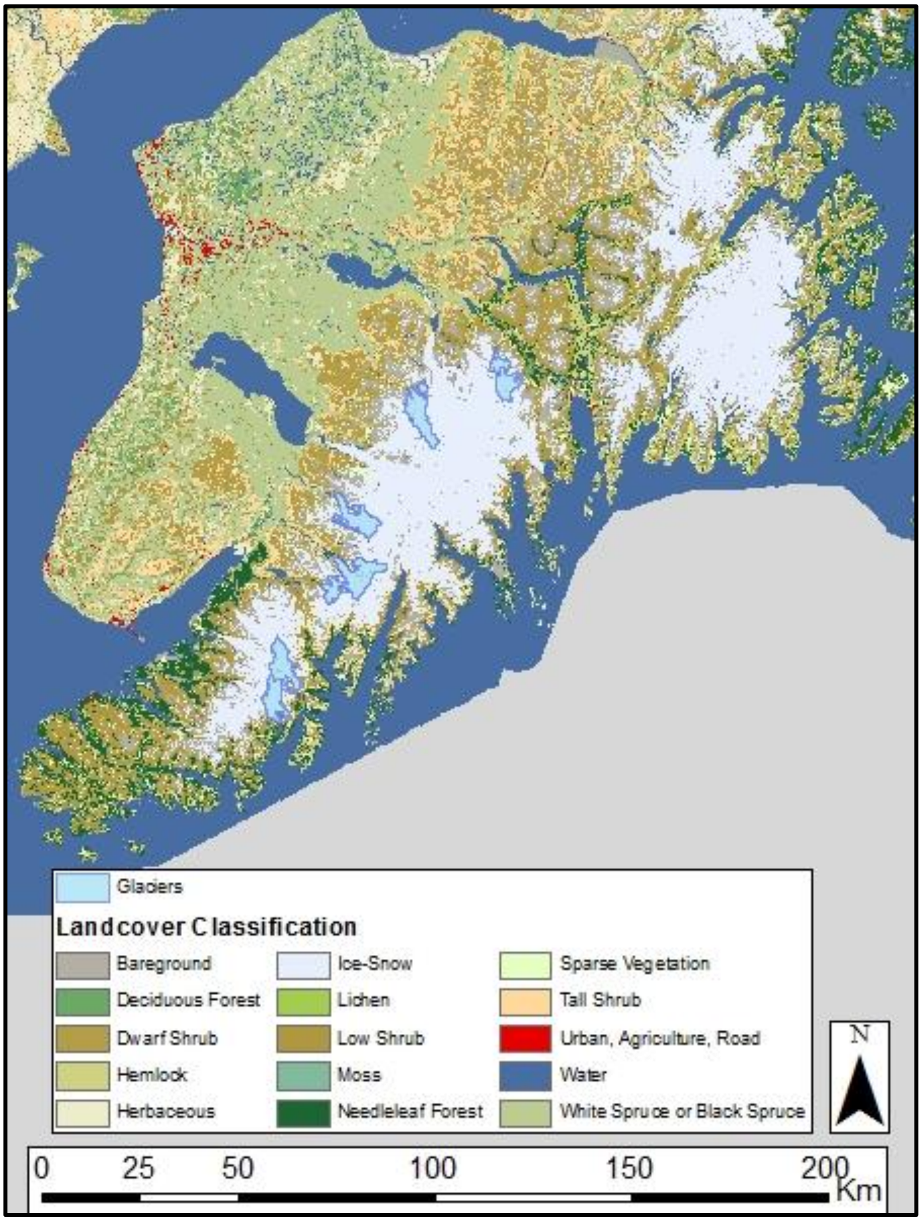


Figure 3: Land cover map of the Kenai Peninsula.
The eight glaciers used in this study are highlighted
(Data adapted from the University of Alaska Anchorage's Alaska Center for Conservation Science)

On March 24th, 1989, the Exxon Valdez oil spill occurred east of the Kenai Peninsula spilling 11 million gallons of crude oil into Prince William Sound. After two weeks, the oil had spread 200 miles and covered the entirety of the peninsula's southern coast. Little over a quarter century has passed and there is little known about what effects this oil spill has had on the glaciers. The ecosystem near the southern coast has started to recover since 1989 but is not to where it was before the spill occurred (Klasner et al. 2009). Some of the vegetation in this study is not only advancing poleward but is also recovering from this catastrophic event that happened over two decades prior.

Alpine tundra best describes the ecosystem near the Harding Icefield and the inland portion of the peninsula, inhabited by mostly low shrubs and dryas communities (See Figure 03). This ecosystem generally sits 600 meters asl. The coastal and lower lying areas such as those near GYGC are characterized by a subalpine ecosystem. This area is further from the glacial complex and at a lower elevation, than the upper montane forest system. These two systems contain shrubs, forest and meadow patches, and aspen or birch trees in the more remote locations. Although these ecosystems contain tall shrubs and trees, areas closer to the glaciers are more barren. With time, the barren land near HI and GYGC are colonized slowly by low-level mosses and lichen then eventually no longer represent an un-vegetated ecosystem. Although all ecosystems in this study contain shrubs and potentially some trees, it is more difficult for vegetation to grow at higher elevations (Dial et al. 2016). This added difficulty in growth is why I hypothesize elevation may play a minor role in the efficiency of vegetative succession in this study.

The Harding Icefield is located on the southeast side of the Kenai Peninsula. HI and its outflowing glaciers cover roughly 2,900 square kilometers making it the largest ice field entirely contained within the United States (National Parks Service 2015). HI's nearly 40 glaciers come in many types and sizes from Bear glacier's 21 kilometer long tongue to the many glaciers with tongues less than 2 kilometers in length. Elevation on the ice field reaches as high as 1,800 meters asl.

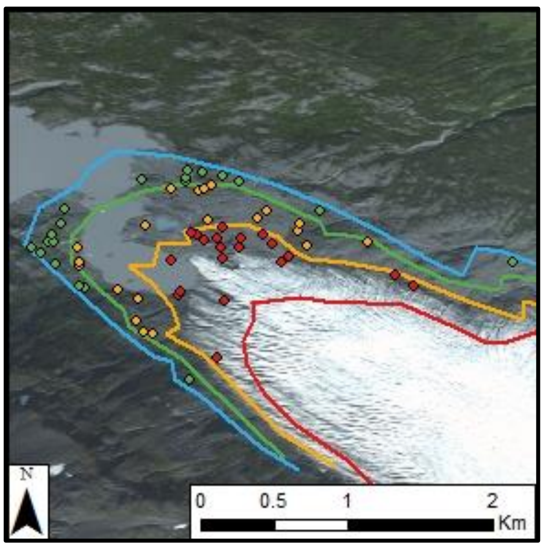
Grewingk-Yalik Glacier Complex sits southwest of HI on the peninsula and reaches elevations similar to those of HI. GYGC covers about 450 square kilometers of land. Although it is almost 25% the size of HI, GYGC lost half the area HI did between 1986 and 2000 (Giffen et al. 2014). All glaciers flowing out from GYGC are land or lake terminating. Elevation on the ice field reaches as high as 1,500 meters asl.

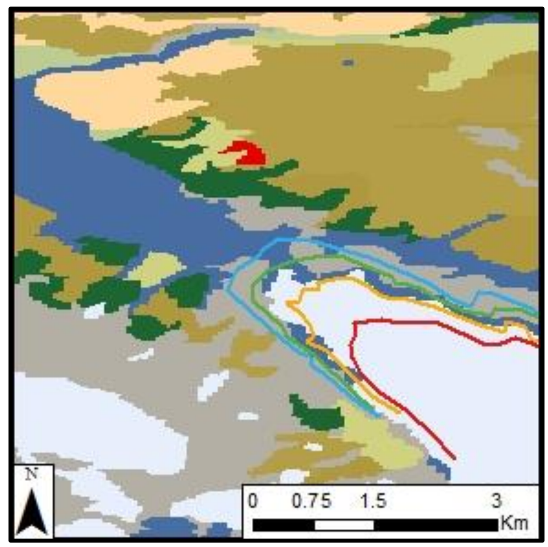
Glacier Overview

Table 2: Elevation of each glacier's foreground

Glacier Name	Average Foreground Elevation (m)	Highest Foreground Elevation (m)	Lowest Foreground Elevation (m)
Dinglestadt	486.87	565.40	448.67
Chernof	714.78	795.22	578.82
Petrof	254.68	315.47	205.44
Yalik	257.96	302.67	195.38
Kachemak	722.98	780.59	668.43
Killey	887.74	941.22	816.56
Lowell	669.99	769.32	588.57
Exit	274.32	430.38	216.10

Dinglestadt glacier (59.754, -150.503) is a lake terminating glacier in the northwest region of HI (See Figure 04). From 1950 to 1985, Dinglestadt glacier retreated 81 meters per year for a total of 2.8 kilometers over the 35-years (See Table 01). This glacier sits at 1,700 meters above sea level at its highest with its foreground averaging 487 meters asl (See table 02). The observed neighboring vegetation to the Dinglestadt foreground is Alder, White Spruce, Sitka Spruce, and Dwarf Shrub (ACCS 2016). Due to their proximity to the Dinglestadt terminus, Alder and Dwarf shrub are expected to be the dominate species in the deglaciated land over the following decades (See Figure 04). These two species should give the maximum NDVI a high value down the line.

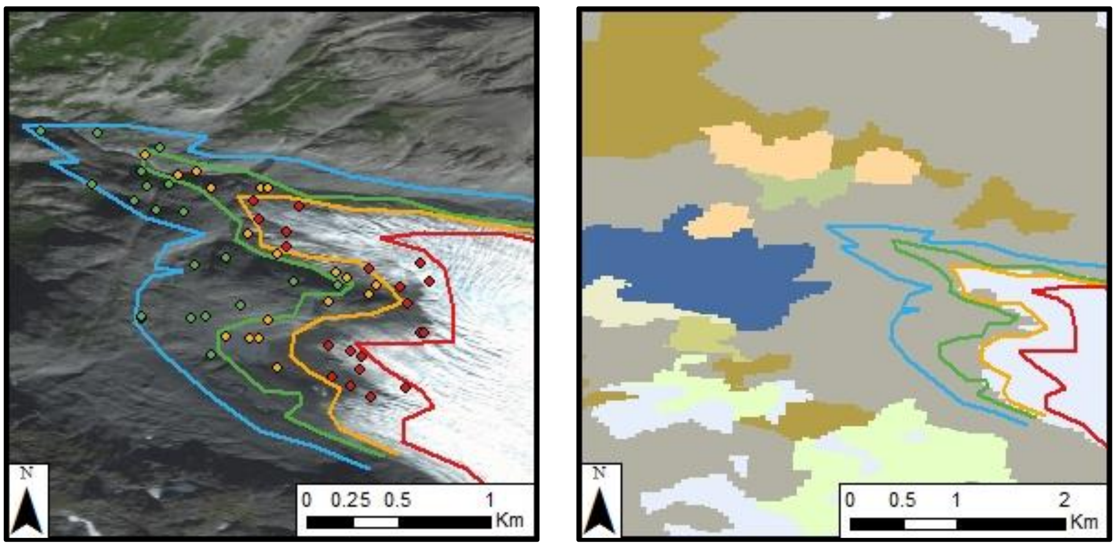




(a) **(b)**

Figure 4: Dinglestadt Glacier tongue.
(a) True color with decadal termini (b) Land cover with decadal termini

Chernof glacier (59.891, -150.486) is a land terminating glacier in the southern region of HI and flows northwest (See Figure 05). From 1950 to 1985, Chernof glacier retreated 39 meters per year for a total of 1,365 meters (See Table 01). This glacier sits at 5,200 meters above sea level at its highest. The foreground at 715 meters giving Chernof the third highest mean elevation of the glaciers observed in this study (See Table 02). The observed neighboring land cover type to the Chernof foreground are deciduous needle leaf forest and Alder within 210 and 425 meters of the observed 1985 terminus (ACCS 2016) (See Figure 05).

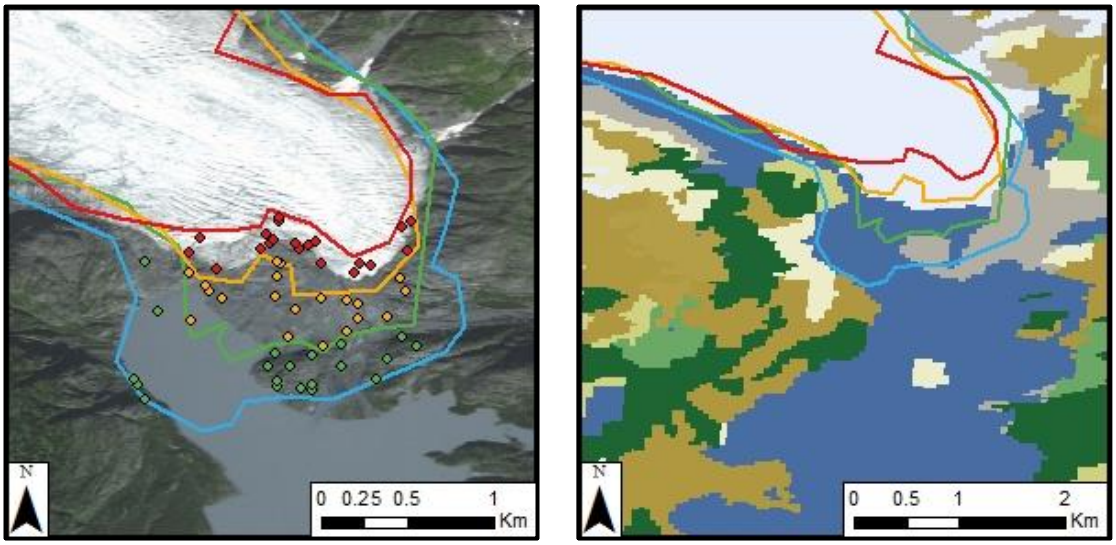


(a) **(b)**

Figure 5: Chernof Glacier tongue.
(a) True color with decadal termini (b) Land cover with decadal termini

Petrof glacier (59.427, -150.850) is a land terminating glacier in the northern region of GYGC (See Figure 06). This is the southernmost glacier studied in this research. From 1950 to 1985, Petrof glacier retreated 36 meters per year for a total of 1.3 kilometers over the 35-year study period (See Table 01). This glacier sits at 1,400 meters above sea level at its highest with the foreground averaging 255 meters. Making Petrof the lowest in elevation glacier observed in this study (See Table 02). The observed neighboring land cover types to the Petrof foreground are Alder-Willow and deciduous needle leaf. (ACCS 2016) (See Figure 06). The foreground of this glacier is only 4.2 kilometers from the Kenai

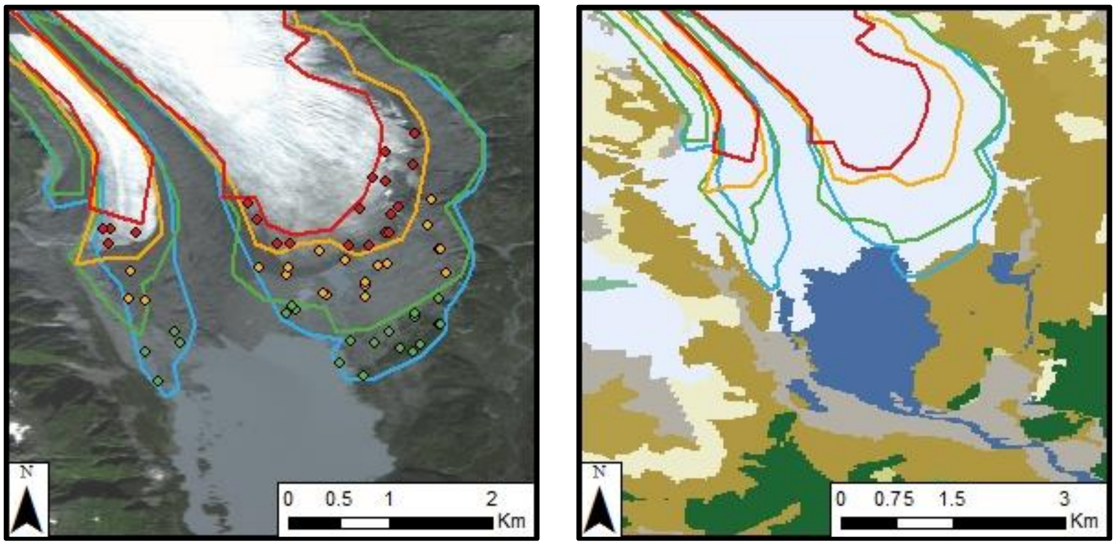
Peninsula southern coast, which is fed warm water from the Alaskan coastal current aiding the growth of Alaska’s south central forested areas (Viereck et al 1992).



(a) **(b)**

Figure 6: Petrof Glacier tongue.
(a) True color with decadal termini (b) Land cover with decadal termini

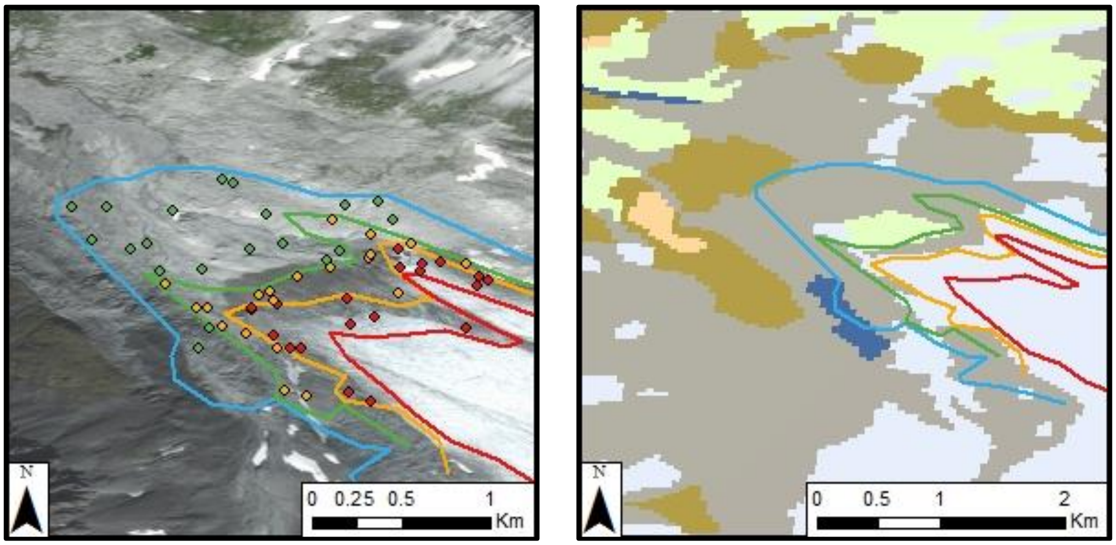
Yalik glacier (59.518, -150.755) is a land and lake-terminating glacier in the northern region of GYGC (See Figure 07). From 1950 to 1985, Yalik glacier retreated 30 meters per year for a total of 1,050 over the 35-year period (See Table 01). This glacier sits at 1,450 meters above sea level at its highest with its foreground ranging from 303 to 195 meters asl (See Table 02). Yalik glacier’s foreground is the lowest in elevation of the glaciers in this study. The observed neighboring land cover types to the Yalik foreground are Alder-Tall Willow, Alder-Low Willow, and Alder (ACCS 2016). Of these three land cover types, the first two are measured to be within the area of the 1985 Yalik terminus (See Figure 07). The foreground of this glacier is 4.7 kilometers from the Kenai Peninsula southern coast, which is fed warm water from the Alaskan Coastal Current aiding the growth of Alaska's south central forested areas.



(a) **(b)**

Figure 7: Yalik Glacier tongue.
(a) True color with decadal termini (b) Land cover with decadal termini

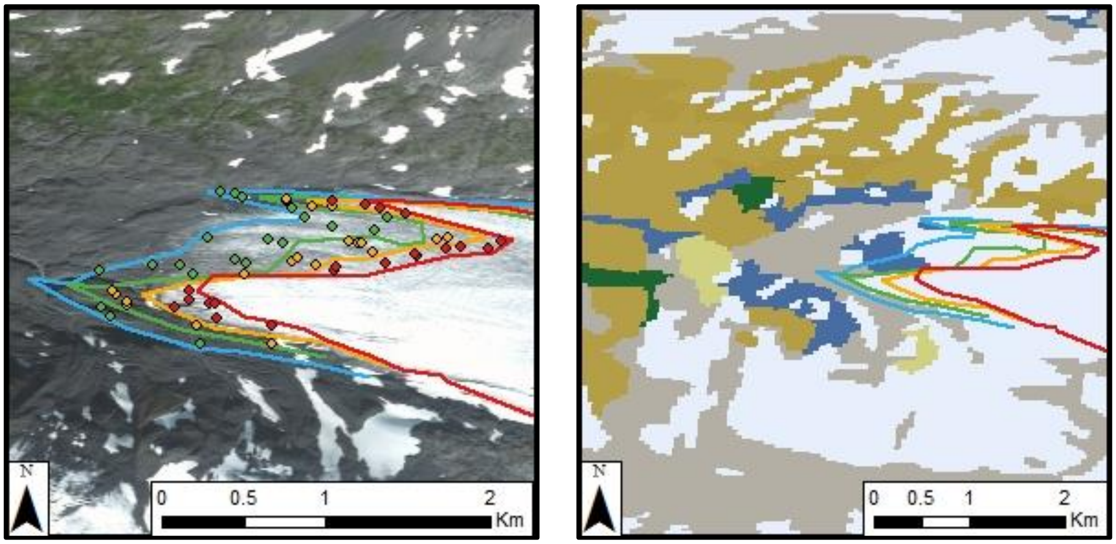
Killey glacier (60.139, -150.140) is a land terminating glacier in the northern region of HI that flows northwest (See Figure 08). From 1950 to 1985, Killey glacier retreated 23 meters per year for a total of 805 meters over the 35-year study period (See Table 01). This glacier sits at 1,600 meters above sea level at its highest with the foreground averaging 888 meters (See Table 02). Killey glacier has the highest foreground of any glacier observed in this study. This high elevation has a strong effect on neighboring vegetation in the foreground. The observed neighboring land cover types to the Killey foreground are Dwarf shrub and Alder (ACCS 2016). The former of these two has already begun to grow within the bounds of the 1985 termini despite the high elevation (See Figure 08). Although there is already vegetation present, the high elevation presumably makes it harder for vegetation to grow leading to a lower overall NDVI.



(a) **(b)**

Figure 8: Killey Glacier tongue.
(a) True color with decadal termini (b) Land cover with decadal termini

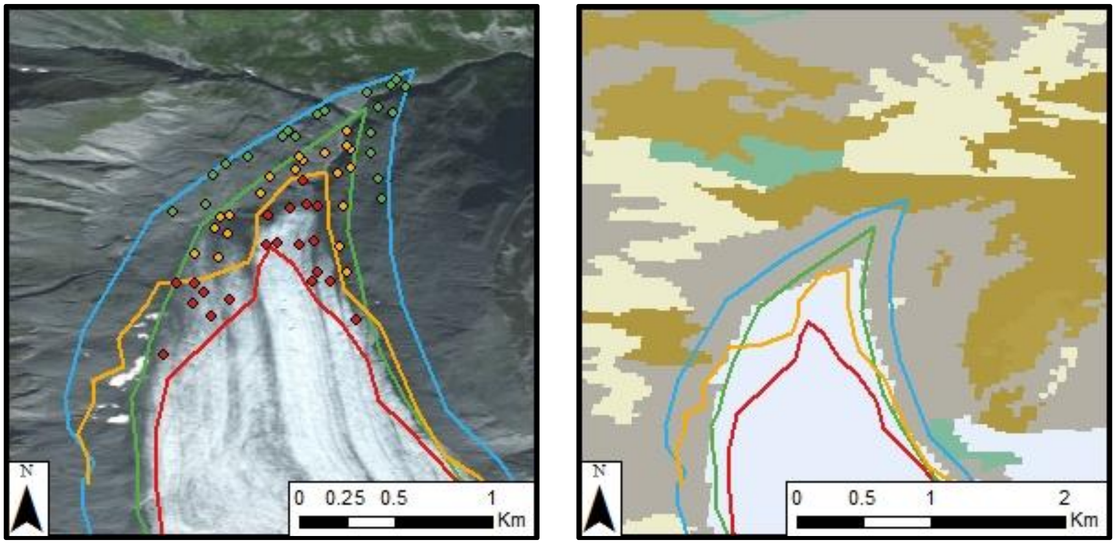
Kachemak glacier (59.690, -150.531) is a land terminating glacier in the southwestern region of HI (See Figure 09). Flowing eastward, Kachemak glacier retreated 23 meters per year from 1950 to 1985 for a total of 805 meters lost over the 35-year period (See Table 01). Kachemak is 1,475 meters above sea level at the highest with its foreground averaging 723 meters asl (See Table 02). The observed neighboring land cover types to the Kachemak foreground are Dwarf shrub and deciduous needle leaf forests (ACCS 2016). Over the 30 years observed in this research, Kachemak's foreground has a high ice presence unlike any of the other glaciers (See Figure 09). Although the NDSI was below the registered snow/ice threshold, upon visual inspection, it appears there is persistent show/ice coverage throughout the study in the immediate deglaciated area. This may cause the NDVI to be unusually low through the duration the course of the study.



(a) **(b)**

Figure 9: Kachemak Glacier tongue.
(a) True color with decadal termini (b) Land cover with decadal termini

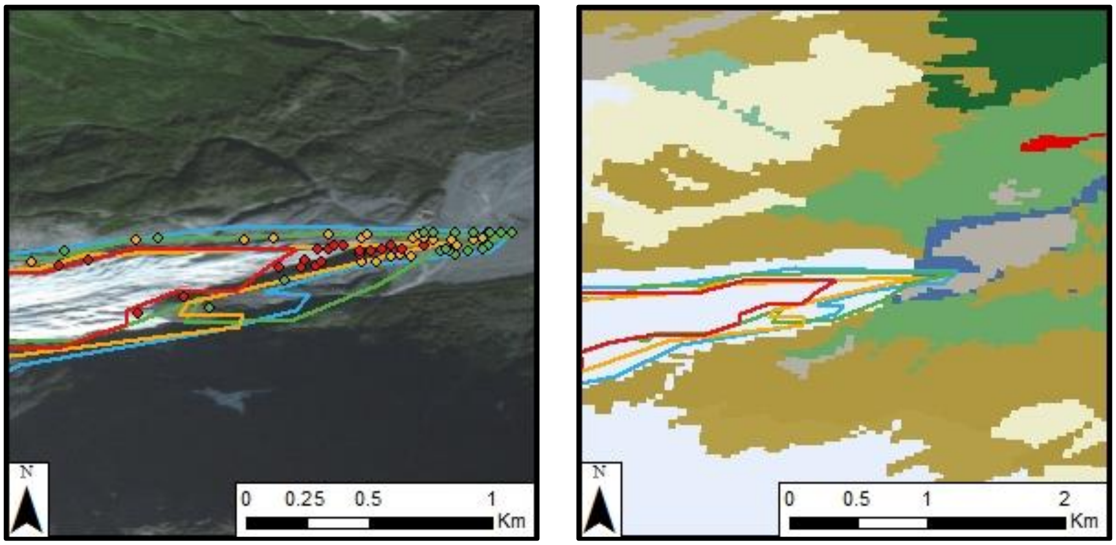
Lowell glacier (60.224, -149.764) is a land terminating glacier in the northeastern region of HI that flows northwards (See Figure 10). This glacier is the northern most observed in the study. From 1950 to 1985, Lowell glacier retreated 21 meters per year for a total of 735 meters lost in the 35 years (See Table 01). This glacier sits at 1,600 meters asl at the highest with its foreground averaging 670 meters (See Table 02). The observed neighboring land cover types to the Lowell foreground are herbaceous Alder and Alder (ACCS 2016). The northernmost tip of the Lowell glacier foreground that was exposed before 1995 already has the presence of vegetation (See Figure 10). This is unexpected from a glacier with such a low retreat rate.



(a) **(b)**

Figure 10: Lowell Glacier tongue.
(a) True color with decadal termini (b) Land cover with decadal termini

Exit glacier (60.175, -149.675) is a land terminating glacier in the northeastern region of HI that lays just 10 kilometers south of Lowell (See Figure 11). From 1950 to 1985, Exit glacier retreated 14 meters per year for a total of 490 over the 35-year study period (See Table 01). This is the slowest observed retreat of any glacier in the study. Exit glacier sits at 1,575 meters above sea level at its highest. The foreground of Exit glacier though averages 274 meters (See Table 02). The observed neighboring land cover types to the Exit foreground are Alder and Black Cottonwood (ACCS 2016). The immediate foreground of Exit glacier is a floodplain, which is very unlike the land cover of each other glacier in this study (See Figure 11). Exit glacier has the most human interaction of any glacier in the Kenai Peninsula. Visitors to Kenai Fjords National Park are able to drive the two lane Exit Glacier Road within two kilometers of the face of Exit glacier. This high level of human interaction and ease of accessibility is one of the reasons that Exit glacier is one of the most studied in southern Alaska.



(a) **(b)**

Figure 11: Exit Glacier tongue.
(a) True color with decadal termini (b) Land cover with decadal termini

The eight glaciers observed in this study all equally represent the land and lake terminating glaciers in both HI and GYGC. With the 1950 to 1985, retreat rates ranging from 14 to 81 meters per year and over 750 meters of elevation change between the highest and lowest deglaciated lands. The land cover classifications closest to HI and GYGC are all represented by the eight glacial foregrounds selected in this project. Utilizing both the *in situ* information gathered from previous studies and Landsat images from 1991 to 2016, I followed the recession of each glacier and the growth of vegetation in each of the glacial foregrounds.

The Kenai Peninsula is home to many species of vegetation all at different stages of succession. Both coniferous and deciduous forests thrive in the region in the absence of major glacial and ice events over the past two centuries.

After a glacier retreats from an area, it leaves bare, soil-less gravel. Over years, moss and lichens begin to grow in the area. They breakdown the rock and create a thin soil layer which will be colonized by smaller shrubs as they begin to expand into the area. Over decades, alder, willows and other tree species will be established. Especially near the southern coast of the peninsula (National Park Service 2015).

Literature Review

The definition of glacier in the most recent IPCC report as an area where climate conditions have allowed snow to persist over one year and compact into ice, traditionally under the force of gravity (Vaughn et al. 2013). Since the Little Ice Age, when the earliest measurements were collected, glaciers have been receding at an accelerating rate. Over time, glacial recession has increased up in all regions around the globe (Pfeffer et al. 2014). The knowledge of glacier-covered areas around the globe is still growing. The Randolph Glacier Inventory, World Glacier Monitoring Service, and Global Land Ice Measurements from Space (GLIMS) project all have cataloged and measured most of the known glaciers on earth. There are roughly 170,000 glaciers covering 0.14% of the Earth's total surface. If melted these glaciers have the ability to raise the sea level roughly 412 millimeters (Marzeion et al. 2012; Pfeffer et al. 2014; Vaughn et al. 2013). Although this is not as dramatic as the threat caused by the melting of the Antarctic or Greenland Ice Sheets, the impact of these glaciers is still significant. In this century, hundreds of glaciers have already disappeared and this rate does not appear to be slowing down.

Cryospheric scientists divide the Earth into 19 different regions (Vaughn et al. 2013). This project focuses in a small portion of the Alaskan region. Overall, this region is highly variable, containing both coastal and inland glaciers as well as partially being within the Arctic Circle (Arendt et al. 2012; Gardner et al. 2013). When performing research, this non-uniformity means that a result of a singular portion of Alaska may not apply to the region as a whole.

Air and land surface temperatures have a direct impact on where and how a glacier melts. As the temperature around a glacier's area rises melt begins to occur. This melt can occur in various ways. It can change the density and thin the ice itself. When ice thins, outside factors have a greater effect on its melt rate causing it to melt faster. Volume and area are two other ways melt occurs in a glacier. These are caused by changes in the outer portion of the glacier gradually moving inwards. Ablation and evaporation also cause glacial melt but at a rate that is insignificant in comparison to the previously mentioned ways (Gardner et al. 2013).

In situ measurements from the 1800's to present day reveal that Alaskan glaciers have experienced decreases in mass, area, and volume (Leclercq and Oerlemans 2012). To measure glacial retreat, *in situ* GPS measurements are commonly used because data such as density is hard to collect remotely. Yet, from a distance, remote sensing is an ideal method to measure retreat. Satellites, airplanes, and most recently drones carrying cameras or special instruments have collected information around the planet for over a century.

From the earliest days of attaching cameras to hot air balloons and airplanes to now using spectroradiometers from satellites, remote sensing is a reliable method to gather information across a wide area. Earth monitoring from satellite images have become an integral part of environmental time series analysis. The push for the Landsat program in the mid 1960's and NASA's Earth Observing System program starting in 1973 propelled daily monitoring of the Earth's surface and atmosphere beyond what was previously capable (Folger 2014).

Satellites have the ability to utilize portions of the electromagnetic spectrum outside of the range observable by humans. By viewing items in not only the visible wavelengths (0.45 – 0.69 micrometers) but also using the mid and shortwave infrared (1.55 – 2.35) and thermal (10.40 – 12.50) portions of the spectrum, one is able to look at the world through a different lens and understand variations the human eye would not. Calculations based on measured satellite reflectance can identify various land cover types, tree types, even the difference between paved and unpaved roads. The Normalized Differential Snow Index (NDSI) utilizes the green (0.55 μm) and shortwave infrared (1.6 μm) wavelengths to identify locations of snow/ice cover. NDSI is described in the following formula (Hall et al. 1995):

$$NDSI = \frac{(Green - Shortwave\ Infrared)}{(Green + Shortwave\ Infrared)}$$

NDSI has been used since the 1970s to discriminate snow from clouds and to track global snow coverage. Traditionally an NDSI above 0.4 registers as snow/ice covered while below that value pixels are recognized as partially covered, barren land, or forest covered. (Klein et al. 1998). MODIS is commonly used to map snow cover because it possesses near global coverage on a daily basis with good spectral characteristics. However, MODIS is not used in this research because its spatial resolution, 250 to 1,000 meters, is too large to identify annual NDSI difference over this study's sites. The sites in this study range from 451.3 meters in length to 1,539.5 meters.

One of the most common uses for remote sensing is to track vegetation abundance, growth, and poleward expansion. Vegetation has well over 100 various indices used globally with the Normalized Differential Vegetation Index (NDVI) being the most common. Much like NDSI, NDVI is developed from data collected in both the visible and near infrared spectrums (Carlson and Ripley 1997). While NDSI uses the green and shortwave infrared wavelengths, NDVI uses the red (0.65 μm) and near infrared (0.80 μm) wavelengths and is computed using the following formula:

$$NDVI = \frac{(Near\ Infrared\ - Red)}{(Near\ Infrared\ +\ Red)}$$

To track the poleward movement of vegetation over wide swaths of the Arctic many researchers have employed annual NDVI time series (Hinzman et al. 2005). Traditionally areas with perineal snow and ice coverage do not contain advanced plant life. Yet, the poleward push of grasses and shrubs allow the sturdier and more resilient plants to move poleward as well. The movements of vegetation have most closely been linked to maximum temperature extremes and less temperatures gradually rising (Cavanaugh et. al 2014). Temperature extremes also have a large impact on glaciers and their melt rate. This factor, amongst many others, links the threat a changing climate has on vegetation and glaciers (Raynolds et al. 2008).

NDVI is not the only vegetation index that has been used in the past. Other works have used the Soil Adjusted Vegetation Index (SAVI), Enhanced Vegetation Index, and the Difference Vegetation Index (Huete 1988; Huete et al. 2007; Richardson and Weigand 1977). Each index has its own benefits and hindrances. The indices all have a landscape they are best suited for and each of these were considered for this study. The Soil Adjusted index was developed to improve sensitivity to soil backgrounds. This would be ideal because this study is looking at initially barren lands but in the deglaciated areas there is little difference between NDVI and SAVI. The Enhanced index is best used for areas with lush vegetation and this study is not experiencing that. The Difference index, like SAVI, is also sensitive to soil but its calculations do not make for easy understanding and lead to much confusion in this study. Each of these indices are used in other projects and have ideal situations but NDVI was chosen because it is the most well-known and widely used of the indices (Xue and Su 2017). This allows for ease of understanding and comparison with other studies.

Poleward advancing vegetation and ice melt are two largely visible ways to see how the Earth's climate has changed overall. Vegetation abundance in Alaska is a growing concern. Plants have a lower albedo than snow or ice and can potentially expand the active soil layer which in turn influences warming of the areas juxtapose to them. There is confirmed evidence of vegetation expansion into the Arctic and it is important to gather knowledge about the causes of vegetation expansion, the rates of this expansion and the most important contributing factors to the expansion (Tape et al. 2006).

The presence of shrubs makes it more difficult for glacial advancement to occur. As glaciers recede, vegetation begins to populate the lands they previously occupied. Identifying the time difference between deglaciation and vegetation expansion can help understand the effects that these processes have on each other. Difficulties in identifying relationships between vegetation growth, glacial melt, and regional warming can be marked with variations in time lags between them (Chapin and Starfield 2007, Jeong et al. 2014).

One of the main factors in arctic greening is temperature change. A 10 to 20 percent increase in peak vegetation greenness has previously been identified to correspond to simultaneous increases in Alaskan tundra temperature increases (Jia et al. 2003). Moving southwards across the Alaskan tundra, summer warmth index and peak NDVI both increase. If this trend continues throughout the entirety of Alaska then the Kenai Peninsula will have some of the highest values recorded in Alaska. The increase in vegetation leads to a decrease in albedo. Regardless of what species it is, all vegetation has a lower albedo than snow or ice meaning all vegetation growth increases the energy absorbed into the region. As increased temperatures help grow more vegetation. More vegetation helps raise the temperature (Beck and Goetz 2011; Loranty et al. 2011).

Traditionally, vegetative succession in glacial foregrounds has been measured using either MODIS or through *in-situ* data collection (Klaar et al. 2015; Nakatsubo et al. 2005). Landsat's higher spatial resolution enables collection of a more precise picture of the changes happening on an annual scale than MODIS and is much less expensive than *in-situ* data collection. By utilizing images collected by the Landsat Thematic Mapper and its successors, my research timeframe is limited to less than four decades beginning with the launch of Landsat 5 in March of 1984. Typically, projects of this nature examine longer deglaciated periods using lower resolution satellite information to cover a larger area (Jones et al. 2003; Raynolds and Walker 2009). This project observed a small area of very recently deglaciated land to examine its immediate regional impact.

CHAPTER II

METHODS

Methods Overview

To examine the relationship between rates of glacial recession and vegetation growth/primary succession eight study sites were selected in the foreground of separate glaciers within the Kenai Peninsula (See Figure 02). The glaciers were selected based on their documented recession rate, their location within the peninsula, and if they were land or lake terminating. Using images from Landsat 5 and Landsat 8, the terminus for each glacier was mapped in the summers (JJA) of 1985, 1995, 2005, and 2015. Landsat 7 images were not used because the scan line error caused great difficulty for digitization in 2005 and 2015. From these four glacier boundaries, three regions in the foreground of each were created. The regions were as follows: deglaciated in 1995, 2005, and 2015.

Twenty points were selected within each region to calculate NDSI, NDVI, and Land Surface Temperature (LST). To ensure uniformity, the points were manually selected to guarantee they did not cover water, were located on slopes less than 15 degrees, and were evenly dispersed within each of the three regions. Using Google Earth Engine (GEE), all summertime (June, July, August) Landsat 5, 7 and 8 top-of-atmosphere brightness values from 1991 to 2016 were collected of each pixel that overlapped the 480 points. The years 1993, 1996, 1997, and 1998 lacked summer Landsat 5 images presumably due to the lack of requests for images over Kenai Peninsula in those years. The missing years were checked on the United States Geological Survey's Earth Explorer website and no images were found in these years. This resulted in the collection of 581 total images. Using NDSI, NDVI, and LST, from the images, the relationship between glacial retreat and succession was identified (See Figure 12).

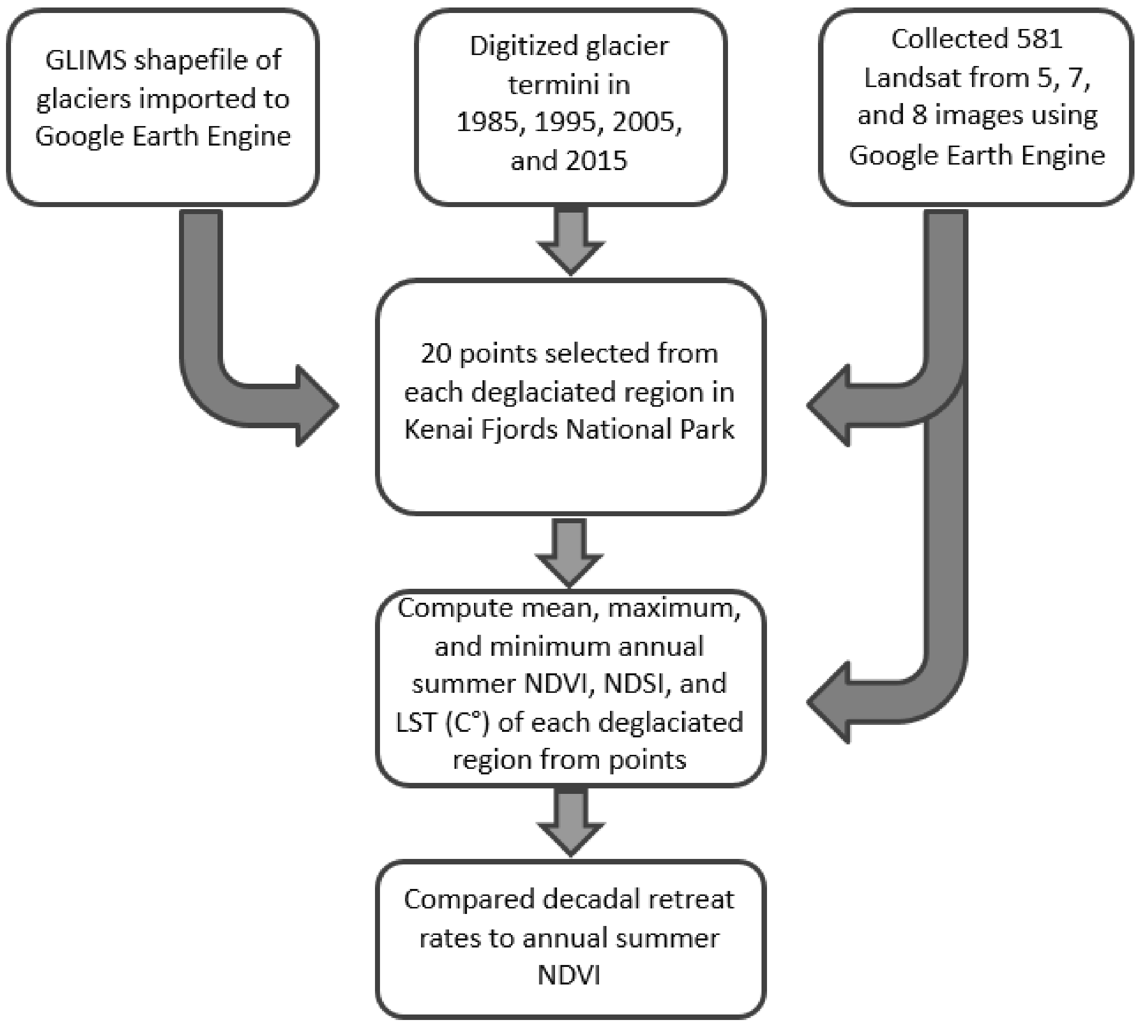


Figure 12: Overview of Methodology

Information on the Glaciers and their Measured Retreat

Most glaciers on the Kenai Peninsula are in the Harding Icefield (HI). This field is in the northeastern portion of the park and is further inland than Grenwick-Yalik Glacier Complex (GYGC). The eastern most glaciers in HI are some of the most accessible glaciers in Alaska, receiving over 100,000 visitors each summer taking the short drive from Seward, AK to see the melting first hand (Curran et al. 2017). The ease of access to HI makes it one of the most visible symbols of glacial melt. HI has lost roughly 10% of its mass since 1950. GYGC, another major icefield on the Kenai Peninsula, has also lost nearly 10% of its mass although it is one-fourth the size of HI (Rampton 2015).

The glaciers chosen represent a range of deglaciation scenarios that occur on the Kenai Peninsula: varying recession rates, land or lake terminating, location within the peninsula, and elevation. The eight glaciers in this study are Dinglestadt, Chernof, Petrof, Yalik, Killey, Kachemak, Lowell, and Exit. All eight glaciers have been monitored since 1950 and some even longer. The GLIMS project and other research has documented the glacial recession rates of the glaciers in both HI and GYGC from 1950 to 2005 even noting that from 1985 to 2000 HI and GYGC lost 2.3 and 2.6 percent of their ice areas, respectively (Giffen et al 2014; Arendt et al. 2012). Previously catalogued glacier extents and measured retreat rates from 1985 to present were not used in this study. Instead, the glacial termini were mapped by hand for the years 1985, 1995, 2005, and 2015 to ensure consistency in mapping. Images from each years' respective summer using Landsat 5 or Landsat 8 top-of-atmosphere 32-day composite was used to map the glaciers (See Table 03). GEE produces the composite images by combining all scenes together from a 32-day period starting with the first day of the year and continuing until the 352nd day (Google 2017). To ensure accuracy on decadal extents these measurements were used to compute linear recession rates between 1985 and 2015.

Table 3: Collection dates for glacial termini in 1985, 1995, 2005, & 2015

Glacier Name	Month of Image Collection			
	1985	**1995**	**2005**	**2015**
Dinglestadt	June 1986	July 1995	June 2005	July 2015
Chernof	September 1985	July 1995	June 2005	September 2015
Petrof	September 1985	September 1995	July 2005	July 2015
Yalik	September 1985	September 1995	July 2005	July 2015
Killey	September 1985	July 1995	June 2005	July 2015
Kachemak	August 1986	July 1995	July 2005	July 2015
Lowell	September 1985	July 1995	June 2005	July 2015
Exit	September 1985	September 1994	Aug 2005	June 2015

Using the images collected, decadal recession of the eight glaciers selected for this project were measured and catalogued. The glaciers selected are ordered from fastest to slowest rate of recession as measured from 1950 to 1985 in Hall et al. 2005.

Dinglestadt glacier is directly south of Chernof and is one of the few lake terminating glaciers in the Harding Icefield (See Figure 02). Dinglestadt has two outlet glaciers, one flowing west and the other east. This research focused on the faster of the two outlets, Dinglestadt west, which will be the only one referred to for the remainder of this paper. Using the 32-day Landsat 5 composite, no cloud-free images were found of Dinglestadt in 1985 so the June 1986 image was used in its place. The 1995, 2005, and 2015 images were all collected in June or July of their correct year (See Table 03). Dinglestadt glacier experienced its fastest change from 1950 to 1985 where it retreated an average of 81 meters per year, the fastest annual rate of any glacier in this study. That annual rate decreased for the following 30 years to 37 meters per year leaving a total recession of 3.9 kilometers since 1950 but only 1.1 kilometers in the past 30 years. From 1985 – 1995, 1995 – 2005, and 2005 – 2015, Dinglestadt glacier receded 256, 352 and 509 meters respectfully (See Table 04). Dinglestadt's tongue receded in a fairly uniform manner over the years, always retaining its rounded frontal form.

Chernof glacier is located in the southern portion of HI flowing northwest (See Figure 02). Due to cloudiness in the 32-day composite, September images of Chernof glacier are used for 1985 and 2015 while 1995's is from July and 2005's is from June (See Table 03). Chernof glacier experienced an annual recession of 39 meters per year from 1950 to 1985. This trend continues in these measurements receding the same average meters per year from 1985 to 2015. Chernof's glacier tongue has receded 1.1 kilometers in the past 30 years and 2.5 kilometers since 1950. From 1985 – 1995, 1995 – 2005, and 2005 – 2015, Chernof glacier receded 347, 364, 453 meters respectfully (See Table 04). The northern portion of the Chernof glacier tongue receded slower than the southern portion causing it to form into the shape of a lopsided "V" over the study period (See Figure 06).

Petrof glacier is the southernmost glacier in this study. It sits near the middle of GYGC flowing southward towards the coast (See Figure 02). Petrof is low in elevation due to its location further south in the peninsula. This is one of the slower melting glaciers in the study between 1985 and 2015 even though it is the furthest south, near the coast, and is at one of the lowest elevations in this study (See Table 03). Visual inspection of the images reveals that the ice appears to remain but is fainter over time, leading me to believe Petrof, is melting more in terms of thinning and less of linear retreat. Petrof glacier still experiences recession but much of the experienced melt is through thickness. Petrof is mainly land terminating yet in the later years a pool has collected. From 1985 – 1995, 1995 – 2005, and 2005 – 2015, Petrof glacier receded 331, 330 and 273 meters respectfully (See Table 04). This lake abuts the western portion of the Petrof glacier foreground before flowing into the Gulf of Alaska.

Yalik glacier is the fastest receding glacier in this study between 1985 and 2015 and lays northeast of Petrof glacier in GYGC (See Figure 02). All images used of Yalik glacier to track decadal recession rate were collected in the correct years (See Table 03). Yalik is classified as both a land and lake-terminating glacier with a tendency to appear as more of a lake terminating one later in the summer (See Figure 10). This lake also flows southward into the Gulf of Alaska near Nuka Bay. Yalik glacier has retreated 2.6 kilometers since 1950 and 60% of that retreat has been within the last 30 years. From 1985 – 1995, 1995 – 2005, and 2005 – 2015, Yalik glacier receded 520, 707, and 313 meters respectfully (See Table 04). This glacier’s largest change was between 1995 and 2005 where Yalik retreated 71 meters per year, only Dinglestadt glacier has a faster retreat rate than that for any period. Yalik’s retreat has been so rapid in parts that the main tongue has disintegrated into multiple pieces giving it the appearance, from satellites, of having two tongues.

Killey glacier is a land terminating glacier on the upper half of HI (See Figure 02). At times the melt and precipitation near Killey may cause the land at the foreground to flood. The floods in Killey glacier's valley are heavy at times due to the higher slopes around it leaving Killey to appear as a lake terminating glacier at times. All images used of Killey glacier to track decadal recession rate were collected in the correct years (See Table 03). Of those in this study, Killey is the fastest receding glacier in HI since 1985, averaging almost 40 meters a year from 1985 to 2015. Killey glacier has receded 2 kilometers since 1950 and 60% of that has been within the past 30 years. From 1985 – 1995, 1995 – 2005, and 2005 – 2015, Killey glacier receded 593, 310, and 292 meters respectfully (See Table 04). Killey's fastest retreat came between 1985 and 1995 where there was almost 60 meters of ice lost per year. The loss of over half a kilometer between those ten years caused a variable retreat pattern in Killey glacier. The terminus started in a curved shape in 1985 but as the retreat continued, the middle began to retreat faster than the edges causing it to become more concave in shape over time.

Kachemak glacier is located on HI's southern half sitting south of both the Dinglestadt and Chernof glaciers (See Figure 02). Visual inspection of the Kachemak glacier valley, Kachemak previously flowed westward but now has turned to flow northwest. From 1985 to 2015, Kachemak is the second slowest receding glacier in this study. Images used for Kachemak come from July of their respective years except the use of August 1986 instead of 1985 (See Table 03). Since 1960, Kachemak has retreated 1.6 kilometers with half of the retreat coming in the last 30 years. From 1985 – 1995, 1995 – 2005, and 2005 – 2015, Kachemak glacier receded 328, 249, and 216 meters respectfully (See Table 04). The center of Kachemak glacier terminus has retreated faster than the sides causing it to forms a concave U shape. This retreat pattern leaves barren soil surrounded by the ice on each side and potentially deters vegetation growth within the concave tongue.

Lowell glacier is the northern most glacier in the HI (See Figure 02). Lowell glacier is a land terminating glacier that, over the study has retreated faster on the sides forming a V shaped terminus. All images used of Lowell glacier to track decadal recession rate were collected in the correct years (See Table 03).

Although the studied foregrounds of Exit and Lowell glaciers are separated by 10 kilometers, these two glaciers have experienced different retreat rates with Lowell retreating at almost twice the pace of Exit. This rate gives Lowell a total retreat of 1.7 kilometers since 1950. From 1985 – 1995, 1995 – 2005, and 2005 – 2015, Lowell glacier receded 236, 346, and 412 meters respectfully (See Table 04). Lowell experienced its highest rate of recession between 2005 and 2015 potentially leading to an even faster rate between 2015 and 2025.

Exit glacier is one of the most commonly visited glaciers in Alaska and even hosted President Barack Obama in 2015. Even though it is the slowest retreating glacier in this study with a total retreat of 0.9 kilometers since 1950, it is still touted as being one of the most visible pieces of climate change in America. Near Exit glacier, there are markers denoting the glacier tongue’s previous position. The 1950 mark sits 0.4 km away from the current location of the glacier.

Three of the four Landsat images were collected in the correct year for Exit glacier but 1994 was used in place of 1995’s image due to spotty cloud coverage over the bulk of the Exit glacier tongue (See Table 03). Exit glacier has an average recession of 14.5 meters per year since 1950. Exit glacier's fastest retreat was from 2005 to 2015 at 30.6 meters per year. This retreat immediately followed a 5-year period where Exit glacier actually advanced 7 meters (Hall et al 2005). From 1985 – 1995, 1995 – 2005, and 2005 – 2015, Exit glacier receded 26.3, 118.6, and 306.4 meters respectfully (See Table 04). At this pace, it is very likely that Exit glacier will begin to retreat at a much faster rate than has previously been recorded. In September of 2017, the area around Exit glacier was closed to visitors due to tall blocks and slabs of ice detaching from the terminus creating an ice fall hazard zone (National Park Service 2017).

Table 4: Glacier Change in meters per year.
***Reprinted from Giffen et al. 2014**

Glacier Name	1950 - 1985*	1985 - 1995	1995 - 2005	2005 - 2015	1950 - 2015*	1985 - 2015
Dinglestadt	-81	-26	-35	-51	-61	-37
Chernof	-39	-35	-36	-45	-39	-39
Petrof	-36	-33	-33	-27	-34	-31
Yalik	-30	-52	-71	-31	-40	-51
Kachemak	-23	-33	-25	-22	-25	-26
Killey	-23	-59	-31	-29	-31	-40
Lowell	-21	-24	-35	-41	-27	-33
Exit	-14	-3	-12	-31	-14	-15

Each glacier was selected because they accurately represent a sample of those found on the peninsula. Although the glaciers have a variety of recession rates and placements on Kenai Peninsula there are also many things they have in common. All glaciers have at least one or two others they are within 10km of, this proximity ensures that the major exterior factors such as encroaching vegetation type, weather, and elevation not too varied.

The Kachemak and Killey foregrounds are the only two located above the elevation cut-off for an alpine tundra ecosystem in the region. Less vegetation is expected there because of the dynamics in this ecosystem. The two glaciers in GYGC are both the lowest in elevation, are nearer the coast, and neighbor traditionally warm, sturdier vegetation in comparison to those in the alpine ecosystem (Stabeno et al. 2016). The glacial foregrounds in GYGC are expected to have the fastest rates of vegetation growth over the 25-year study period. The other glaciers in the study are between 250 and 600 meters in a subalpine ecosystem, a better representation of the ecosystem surrounding HI.

Data Sources

The data collection used in this study encompassed the summertime Landsat images acquired between 1991 and 2016 over the southern portion of Kenai Peninsula. Using traditional remote sensing processing techniques, data processing would traditionally take weeks or months of work to accomplish and requires terabytes of data storage. To minimize the time and storage required, Google's Earth Engine cloud computing platform was used in the analysis (Gorelick et al. 2017). Each Landsat image can be modified and coupled with elevation, land cover, or climate data to perform projects and solve GIS related issues around the globe. Previously, Google Earth Engine's abilities have been utilized on projects to develop high-resolution maps of global surface water occurrence, survey over a decade of global tree cover extent and change, and track changes and prevent loss to critical endangered wild tiger habitats (Gorelick et al. 2017; Hansen et al. 2013; Pekel et al. 2016; Joshi et al. 2016).

Google Earth Engine is a powerful computing tool with high ease of access. It uses JavaScript in a user-friendly interface that can be switched to a Python program interface if the user desires. Individual users may also access their Google drive storage to upload personal data and relate it to any data Earth Engine has. Unlike most remote sensing programs, Earth Engine is also accessible by any device with an internet connection. A cell phone or small laptop could be used to view data while out of the office. This said, Google Earth Engine is still limited in the number of things it can do. Exporting maps and tables are time consuming and may take more than a few hours to get small maps created. This program is still relatively new and has bugs but with help from the developers group, most issues can be solved.

In this study, Google Earth Engine's access to Landsat 5 and Landsat 8 images were used to map the various termini of each glacier in the years studied. These images were 32-day top of atmosphere reflectance composites developed by Google based on standard Landsat processing approaches (Gorelick et al. 2017). Landsat 5 and 8 were used to map the glacier boundary each ten years to avoid complications with the Landsat 7 scan-line error problems. With the exception of Dinglestadt and Kachemak glaciers in 1986 and Exit glacier in 1994, all images used to measure the glacier bounds were taken in their respective years.

Following the delineation of the glacier foregrounds for the three periods, 480 points were selected with the following criteria: not covering any water between 1991 and 2016 evenly spread out over the recently deglaciated region, and no slope above 15 degrees. The first two criteria were accomplished using Landsat images and the third was resolved with the Global Multi-resolution Terrain Elevation Data 2010 dataset available within GEE. This version of the data has a 7.5 arc-second (approximately 250m) resolution. The more common and higher resolution Shuttle Radar Topography Mission dataset was not useable due to its maximum latitude of 60°N and Exit, Lowell, and Killey glaciers are all north of 60°.

All elevation data used in this project outside of GEE was received from the National Elevation Dataset (NED). A 30-meter digital elevation model from NED, over Alaska, was obtained through the Alaska Geospatial Council website. Information from the raster is used throughout this project to identify elevations of glacial foregrounds and changes over the glacier area (Alaska Geospatial Council 2017; Gesch et al. 2002).

The top-of-atmosphere brightness values from each of the 480 sample points were extracted from the 581 Landsat images called between June 1st and August 31st of each year. The Path/Row of the images used in the study were 68/18, 68/19, 69/18, and 69/19. Approximately 10,600 data points were extracted for each glacier spanning the 25-year study period. Land Surface Temperature (LST) at each point was determined from the Landsat thermal bands. As Landsat 7 and 8 have two separate thermal bands, the band most closely approximating Landsat 5 single thermal channel (band 6) was selected for consistency. Significantly low thermal brightness temperatures or high reflectance in other bands were flagged as potential errors. These errors were only spotted after 2003. This is the year Landsat 7 started experiencing a scan-line error.

The mean, maximum and minimum of NDSI, NDVI and LST for each section in each year were determined from the observations. Following the extraction of all information in GEE, the R statistical program (version 4.3) was used to analyze and visualize the extracted information (R Core Team 2013). ArcGIS (version 10.3) was used for mapping and selected spatial analysis.

CHAPTER III

RESULTS

Expected Results

This project separated the deglaciated region of eight glaciers into three then placed 20 points within each region. Totaling 480 points over 24 regions for the entire study. The Landsat brightness values were collected for the summer values from 1991 to 2016 of each point. Two indices were calculated from the points, NDSI and NDVI, with LST taken from the Thermal bands of Landsat. With these three values over the foregrounds of eight different glaciers, the research questions are answered.

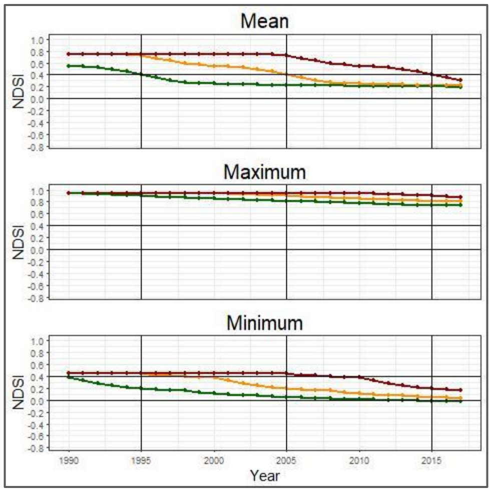
In remote sensing, an area is recognized as snow/ice free once the NDSI is below 0.4 (Klein et al. 1998). Because of how the point collection was done, average and minimum NDSI are expected to be below 0.4 all years after a region is recognized as fully deglaciated (See Figures 13 & 14). The mean NDSI is the combined response of snow and ice cover over the summer months. Minimum NDSI, on the other hand, is representative of the single day each summer where the lowest amount of snow or ice is registered. Because of the nature of both the mean and minimum NDSI the mean NDSI is expected to be more responsive to overall changes in the landscape while minimum will be more responsive to atypical events happening over the course of a summer. Mean NDSI values are predicted to follow an inverse pattern to the LST. As each region passes the year it was measured as officially deglaciated, 1995, 2005, and 2015, mean NDSI should be representative of non-snow/ice covered, barren land (NDSI ≤ 0.4) (Klein et al. 1998). The vegetative response should follow the NDSI's reaction to the temperature.

The faster retreating glaciers, those classified as averaging more than 30 meters or more of linear retreat per year between 1950 and 1985, are expected to have an earlier positive vegetative response (NDVI ≥ 0.2) than their slower retreating counterparts (See Table 04) (Klein et al. 1998). Once the NDSI decreases past the traditional 0.4 threshold for ice, the mean NDVI values should be above 0.2 within a decade for the faster retreating glaciers and 15 years for slower retreating glaciers. Regardless of the rate of recession, NDVI is expected to see an increase that is initially gradual then heightened and eventually leveling out until the next step in the succession process. Much like the mean and minimum NDSI, mean and maximum NDVI have separate representations of the foreground. The mean NDVI represents the general coverage of moss, shrubs, or trees over the area while maximum NDVI represents the date of peak vegetative activity. Average NDVI is expected to start an increase while NDSI is decreasing but to increase in growth rate once vegetation is established (Jeong et al. 2013). The succession pattern, from moss to eventual trees, is expected to be observed as a step-wise pattern in the NDVI graph. This step-wise pattern is also expected to be better defined for the faster retreating glaciers than the slower retreating glaciers (See Figures 13 & 14).

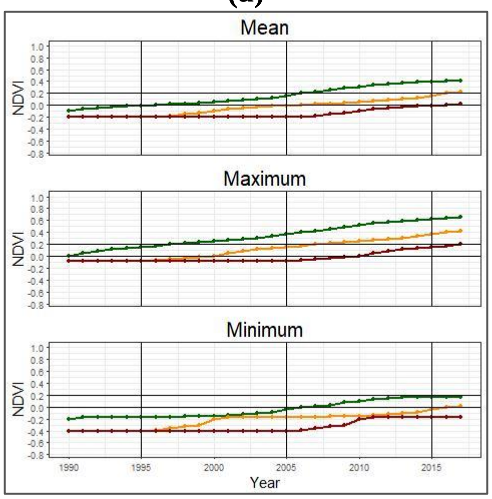
The region deglaciated between 1985 and 1995 for each glacier should have an average LST above 0°C after 1995 and increase as the permafrost continues to thaw (Jeong et al. 2013). While the vegetation advances into the foreground, temperature is expected to rise faster, then level out as the NDVI evens out as well. The other two regions' LST should start at or below freezing but should reach temperatures above 0°C as each of their regions deglaciated (See Figures 13 & 14). The average LST of the total observed foreground is expected to be positive by 2016 as the third region deglaciates. While LST is expected to be recognized as above freezing once a region deglaciates, the increase in temperature between fast and slow retreating glaciers should be evident. The nearness of a slow retreating glaciers to the study area affects the land surface temperature making it noticeably colder than the foreground of the faster retreating neighbors.

A little over a decade after crossing the NDSI snow cover limit, NDVI's response for slow retreating glaciers is expected to be above 0.2. The ice melt and vegetation growth of slower retreating glaciers should be less responsive to temperature than their faster retreating neighbors' should. With slower retreat, the lingering colder temperatures from the glacier would add difficulty in vegetative growth preventing an increase of energy absorption into the newly barren soil. This process would slow the feedback loop from increasing regional temperature and energy absorption.

The maximum NDVI and NDSI are expected to reveal much new information much like minimum values. In alignment with some papers, the maximum temperature was calculated to identify potential times for major vegetation growth or massive ice-loss; both were recognized as having shaper responses to temperature extremes (Blok et al. 2011).



(a)



(c)

Figure 13: Expected results of foreground for fast retreating glaciers (a) NDSI (c) NDVI (e) LST
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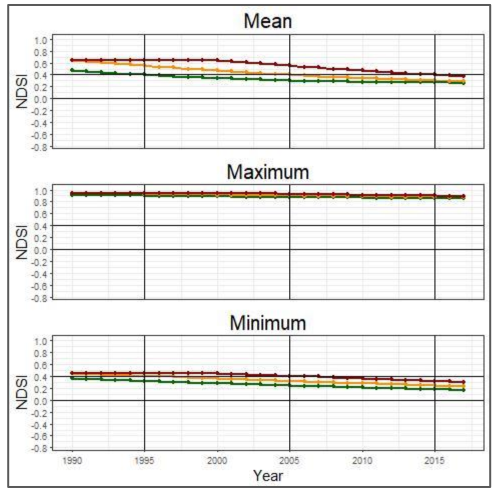

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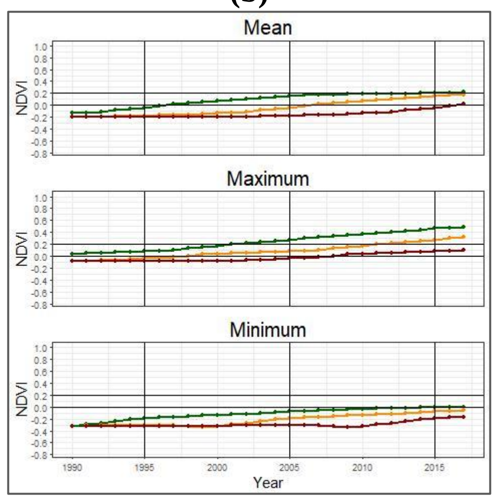

(d)

Figure 14: Expected results of foreground for slow retreating glaciers (b) NDSI (d) NDVI (f) LST
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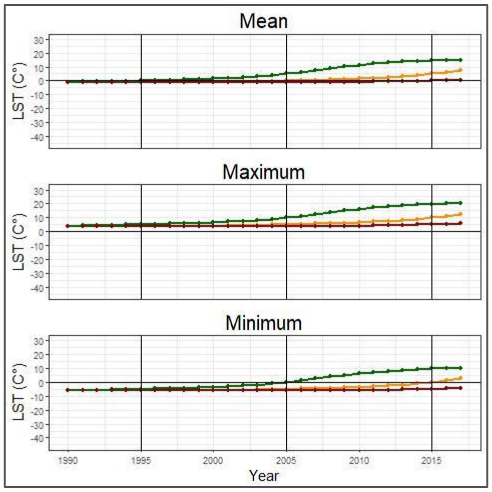
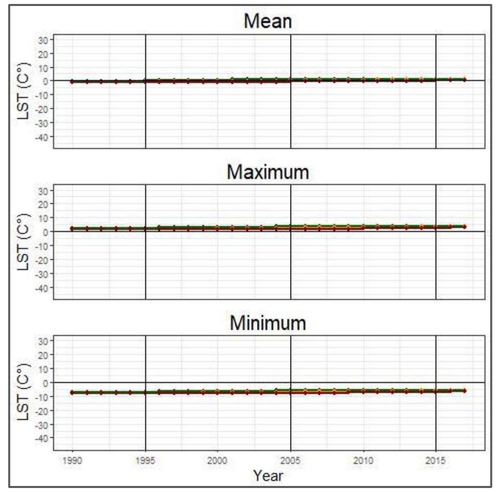


(e)
Figure 13 continued



(f)
Figure 14 continued

Individual Glaciers

The eight glaciers in this study are organized by the measured retreat rate from 1950 to 1985 in Hall et al. 2005. The following results explain the NDVI, NDSI, and LST of each glacier's foreground as well as how the values relate to one another. Separate vegetation types have different NDVI. The difference in vegetation between the glacial foregrounds have an effect on the intensity of the NDVI response and how quickly the vegetation will react to new, ice-free areas. The NDVI of higher elevation foregrounds are expected to be lower than their lower elevation neighbors. Elevation also has an effect on NDSI and LST. Traditionally, higher elevation areas have a lower temperature and longer lasting snow and ice. A third factor is distance from the coast. The nearer a foreground is to the coast, the lower the elevation is and the more effective the warm air from the Alaskan Coastal Current is on the LST.

The following section outlines the mean, maximum and minimum NDVI, NDSI and LST of the eight glacial foregrounds. Each of the adjoining plots have the three regions of each glacial foreground separated by color. The region deglaciated between 1985 and 1995 is green, the region deglaciated between 1995 and 2005 is orange, and the region deglaciated between 2005 and 2015 is red. Each of the plots have vertical lines noting the years each of the regions deglaciated, 1995, 2005 and 2015. The NDVI plots have horizontal lines marking the 0 and 0.2 thresholds. The NDSI plots have horizontal lines marking the 0 and 0.4 thresholds. While, the LST plots have horizontal lines marking the 0°C threshold for freezing.

The NDVI of each glacier was also compared to the maximum LST and minimum NDSI. These relations show vegetation's response to high temperatures and low snow/ice coverage. Maximum LST and minimum NDSI were chosen because they both had the most direct relationship to NDVI. On some level, the vegetation of all eight foregrounds are related to temperature and snow/ice coverage and are paramount to understanding the NDVI response.

Dinglestadt Glacier

With almost 4 kilometers of total retreat since 1950, Dinglestadt glacier is the most active in this study. The 60 points selected to cover the foreground spread in elevation from 1,855 meters to 1,472 meters averaging 1,597.4 meters (Gesch et al. 2002). Dinglestadt's tongue flows northwest, the western portion of the foreground holds a lake feed by the tongue while the eastern portion is open land. For Dinglestadt, most of the points selected were on the eastern portion to ensure all pixels were consistently non-water covered. After having 81 meters of retreat per year between 1950 and 1985, Dinglestadt had a slowdown losing 26, 35 and 51 meters per year of the next three decades (See Table 04).

Dinglestadt glacier's increase in retreat rate is visible in the mean and maximum NDVI charts (See Figure 15). The oldest deglaciated region, that took the longest to retreat, did not achieve an average NDVI value above 0.2 until 2013. Almost a full 20 years after the area was fully deglaciated. The maximum NDVI measurement surpassed the 0.2 threshold in 1999, just 4 years after the region was full deglaciated. After passing the 0.2 threshold, the NDVI continued to rise where it reached 0.78 in 2016. The second deglaciated region does not have a year where the average NDVI surpassed the accepted threshold but is on the same trend as the earlier deglaciated area. In 2006, this area's maximum NDVI value passed the 0.2 threshold and stayed above for the remainder of the study. The values stayed on an upward trend eventually reaching 0.66 in 2016. As expected, the mean NDVI of the most recent deglaciated region possessed negative, or near negative values for the duration of the study. The maximum NDVI values of this study only surpassed the NDVI threshold 9 times during this study, 4 of the times while glaciated.

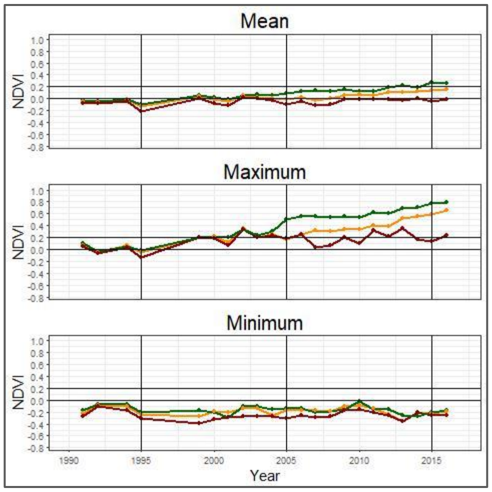
After 1995, the longest deglaciated region has only experienced one year of high NDSI (See Figure 15). The second region shows 2 years of mean NDSI above 0.4 post-deglaciated and the newest deglaciated region does not have any years. After deglaciation, the minimum NDSI of the Dinglestadt glacier foreground was 0.05 or below.

The LST of Dinglestadt's oldest deglaciated region has temperatures mostly above 0°C with only 4 years averaging negative land surface temperatures (See Figure 15). The following deglaciated region has consistent average temperatures above freezing for most years after deglaciation in 2005. The most recently deglaciated area of Dinglestadt's foreground has only one-year post deglaciation and it is at 4.0°C. For the study area of the foreground, maximum LST were at least 12.9°C after deglaciation.

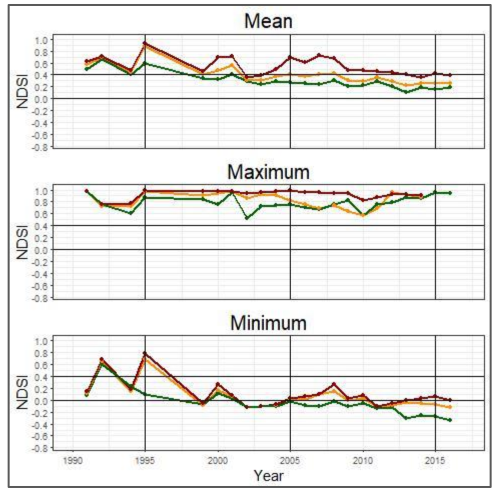
The effect of maximum LST on NDVI over the Dinglestadt foreground reveals differences on how separate areas behave after prolonged exposure to open air and vegetation (See Figure 15). All three points that have an average NDVI greater than 0.2 (2013, 2015, 2016) also have maximum LST above 20°C. The recently deglaciated region was the only one where NDVI values greater than 0.2 have LST readings below 10°C.

The relationship between NDVI and minimum NDSI in the Dinglestadt foreground has a similar result to NDVI's response to maximum LST (See Figure 15). Most minimum NDSI responses collected are below the 0.4 threshold regardless of glaciation status. Of the years where maximum NDVI was greater than 0.2 and minimum NDSI was greater than 0 there is one in the oldest deglaciated region (2000, 2001), six in the second region (2005-2010), and three in the newest region (2006, 2009, 2016). All other times maximum NDVI is greater than 0.2 the minimum NDSI is less than zero.

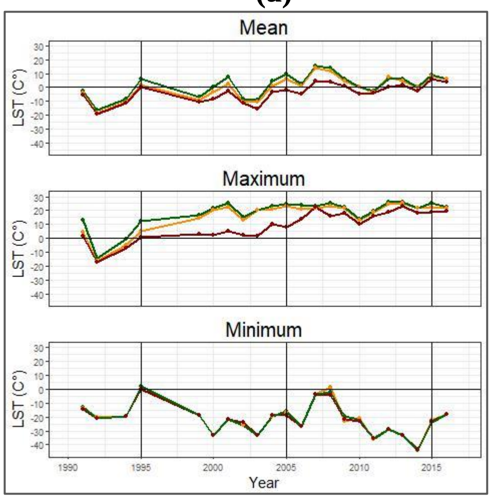
Dinglestadt's three deglaciated regions in this study have increasing retreat rates and varying vegetation growth rates. The relationship between NDVI, minimum NDSI, and maximum LST has the faster retreating region behaving as if it had retreated five years sooner. Mean and maximum NDVI of the Dinglestadt glacier foreground closely mimic a 10-year delay between each region as was expected.



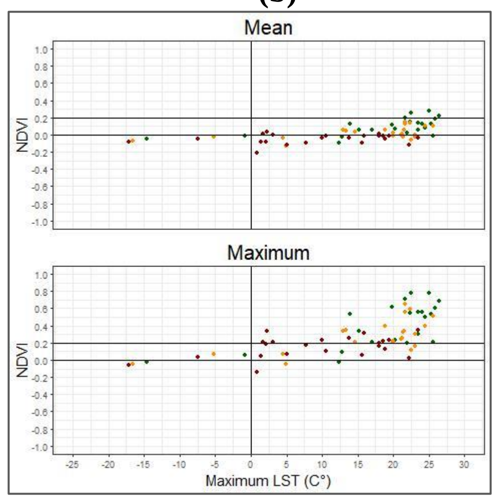
(a)



(b)



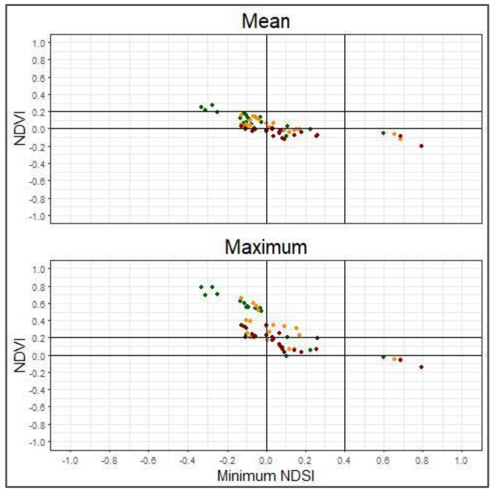
(c)



(d)

Figure 15: Results of Dinglestadt Foreground.
(a) NDVI (b) NDSI (c) LST
(d) NDVI vs. Maximum LST (e) NDVI vs. Minimum NDSI

Continued on following page



(e)

Figure 15 continued

Chernof Glacier

Since 1950, Chernof glacier has a total retreat of 2.5 kilometers. The third most of the glaciers in this study. The 60 points collected in the Chernof foreground average 2,345.1 meters in elevation with a total range between 2,609 meters and 1,899 meters (Gesch et al. 2002). The Chernof glacial tongue flows northwest with the northern part of the tongue retreating slower than the southern part. From 1950 to 1985, Chernof glacier was the fastest retreating, land terminating glacier in this study with 39 meters of retreat per year. Over the following 30 years, Chernof glacier had similar retreat rates. The following three decades have retreats of 35, 36 and 45 meters of retreat per year.

The average NDVI of any region in Chernof's deglaciated zone never surpassed 0.1. Although the NDVI of the foreground is low over the 25-year period, each region follows a 10-year lag for growth as each region deglaciates (See Figure 16). The maximum NDVI of the oldest deglaciated region did not have consecutive years above 0.2 until 2004, 9 years after the region was officially deglaciated. Following a similar trend, the middle deglaciated region did not stay above the NDVI threshold until 8 years following deglaciation in 2013. The two most recently deglaciated regions follow a near identical sinusoidal pattern from 1999 to 2010 where they pass well above the NDVI threshold every other year. A similar pattern is seen in the early years for minimum NDSI but in no other output.

Mean NDSI of Chernof glacier is below the snow/ice threshold for each year post-deglaciation in the oldest and most recent deglaciated zones. Post-deglaciation, the second deglaciated zone has five years where the NDSI averages above 0.4 and the NDSI never drops below 0.33 over the duration of the study (See Figure 16). The minimum NDSI of Chernof's foreground followed a sinusoidal pattern from 2000 to 2005 that resembled the previously mentioned NDVI pattern.

Of the 18 recorded years after deglaciation, Chernof's oldest region has experienced 8 years of average LST below 0°C. The most recent negative temperature year was 2014 with an average temperature of 1.76°C (See Figure 16). Chernof also has one of the lowest post-deglaciation maximum LSTs as well with 11.66°C occurring in 2002 for the oldest deglaciated region. The average temperatures of the other two regions do not stray far from this path with 4 out of 11 negative years for the second region and the lone negative year for the third region.

The maximum NDVI vs maximum LST chart shows how each of the three regions differ while all having similar retreat rates. The oldest region has values above 10°C in all years while the other two have decreasingly lower land surface temperature values (See Figure 16). The two most recently deglaciated zones have years with maximum temperatures below 10°C but NDVI above 0.2. This is from the years where the annual maximum NDVI was following a sinusoidal pattern.

The NDVI and minimum NDSI did not have a similar pattern though. All maximum NDVI above 0.2 and average NDVI above zero years still have minimum NDSI blow 0.4 (See Figure 16). When minimum NDSI is below zero for the longest deglaciated region there is also a near 100 percent chance the maximum NDVI is above 0.2 as well.

Chernof glacier is a constantly retreating glacier averaging 38.91 meters of retreat per year from 1950 to 2015. Although the retreat rate of Chernof is high, it is also one of the highest glaciers in HI and the third highest in this study. The high altitude of Chernof puts different vegetation in the area than the lower lying Exit or Dinglestadt glaciers. This elevation also effects how quickly the vegetation advances and other factors. The NDVI is effected more by the elevation than the NDSI or LST.

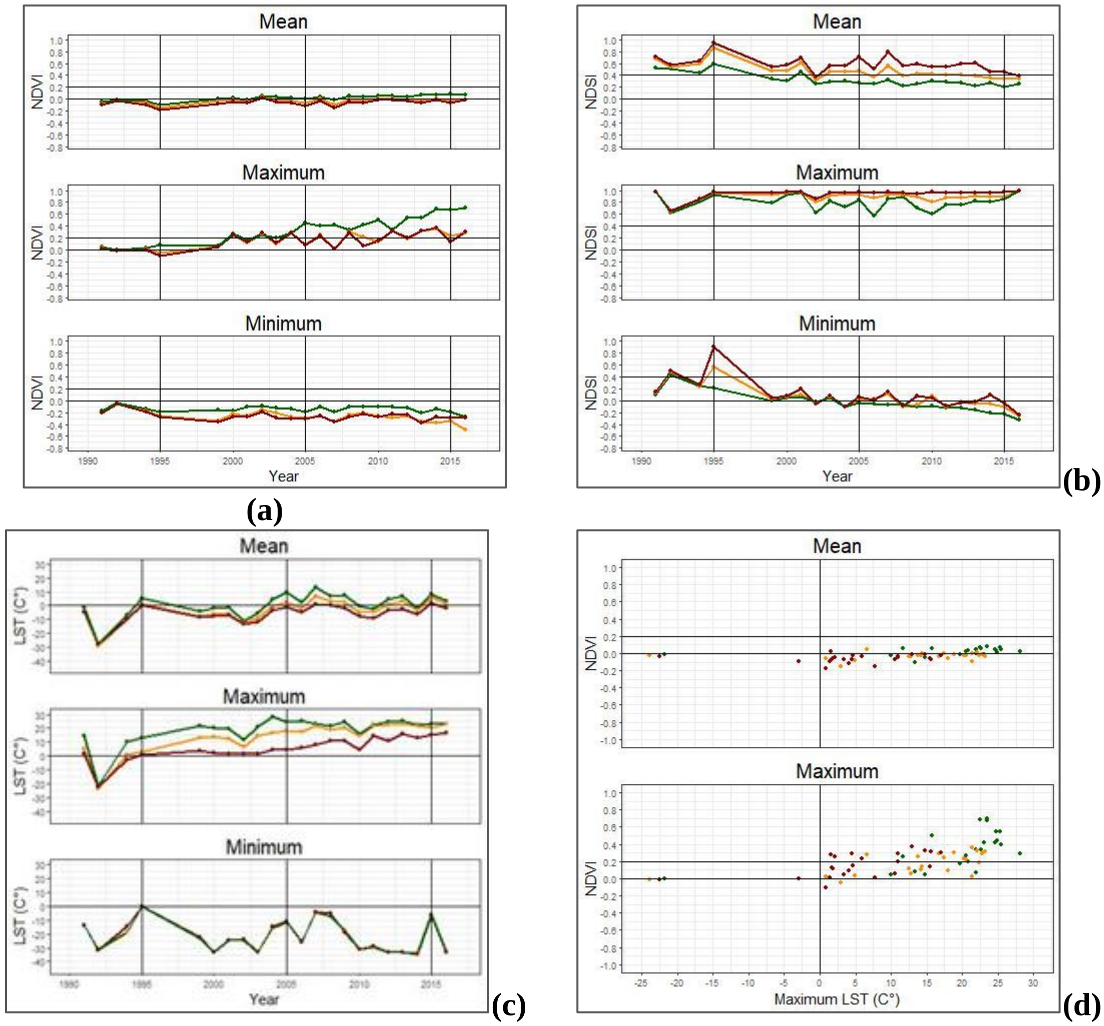
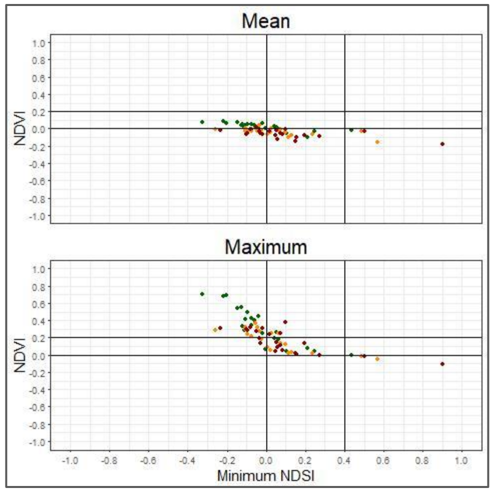


Figure 16: Results of Chernof Foreground.
(a) NDVI (b) NDSI (c) LST
(d) NDVI vs. Maximum LST (e) NDVI vs. Minimum NDSI
Continued on following page



(e)
Figure 16 continued

Petrof Glacier

Petrof glacier is the southernmost glacier in this study. Also, with the Petrof foreground ranging between 1,035 and 674 meters it is the lowest glacier in elevation (Gesch et al. 2002). Of the eight glaciers in this project, Petrof has the fourth largest retreat since 1950 with over 2 kilometers of melt yet possess the third slowest retreat since 1985, after Exit and Kachemak glaciers. The 36 meters of ice lost per year gave Petrof a quick start between 1950 and 1985 but between 1985 and 2015 the glacier average only 31 meters of loss per year. Petrof lost 33, 33 and 27 average meters of retreat each decade. The decreasing retreat rate is not common in this study.

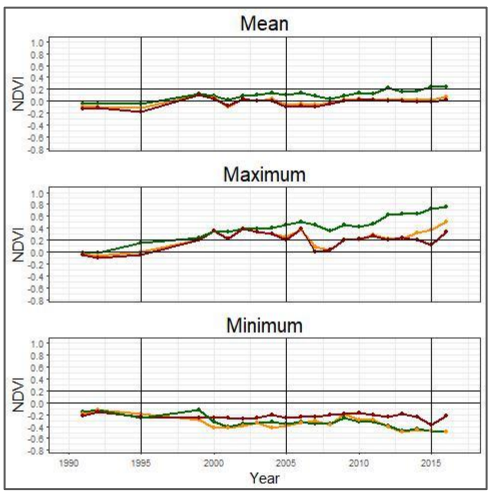
Petrof glacier does not have a strong NDVI response over the 25 years in this study. In all three regions, only three years (2012, 2015, 2016) of the oldest region has an above 0.2 average NDVI value (See Figure 17). Although the average NDVI is low, the maximum NDVI is above the 0.2 threshold for each region post deglaciation with peak values of 0.76, 0.50, and 0.39 for each region respectively. Petrof's high maximum but low average values are potentially a factor of the decreasing retreat rate over the decades.

Petrof glacier's NDSI response over the deglaciated regions was beneath 0.4 after recession. Petrof glacier's longest deglaciated region has some of the lowest NDSI minimums of any glacier in this study (See Figure 17). The years 2001 and 2007 had spikes in minimum NDSI for the most recently deglaciated region of Petrof glacier. In the region both years were followed with an immediate decrease roughly matching the magnitude of its increase.

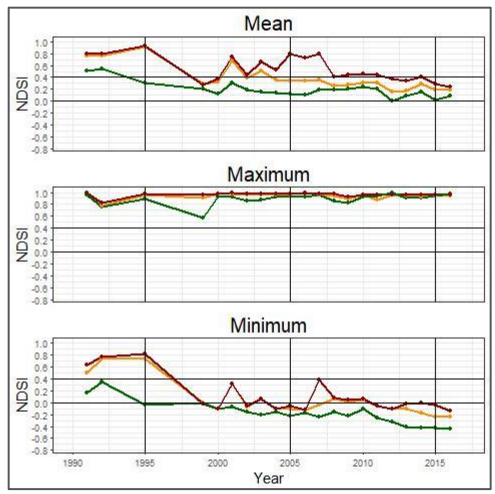
Both the average and maximum Land Surface Temperatures in the Petrof glacier foreground is lower than most other foregrounds in this study. Yet, when compared to the NDVI, the Petrof foreground follows the same pattern of having only maximum NDVI responses above 0.2 match with maximum temperatures above 10°C (See Figure 17). Similar to the previous glaciers, the deglaciated regions are separated into recognizable clumps near one another. Between the three regions, no maximum NDVI above 0.2 has a maximum temperature below 0°C.

The mean and maximum NDVI vs minimum NDSI charts very well fit the model of a swiftly retreating glacier. Almost all positive vegetative responses fit below where minimum NDSI was less than zero (See Figure 17). The NDVI relationship to maximum LST is not as strong as the minimum NDSI relationship but still follows an expected pattern (See Figure 17). Like the other fast retreating glaciers, NDVI is seen to be directly related to both minimum NDSI and maximum LST.

Petrof glacier has a slowing retreat rate for each decade between 1985 and 2015. Although there are high maximum NDVI and low NDSI values for each region post deglaciation, Petrof glacier's foreground LST is lower than glaciers at higher altitudes. The slower retreat rate possibly has a direct effect on how much lower Petrof's LST is than other glaciers. Without the inclusion of the slowing retreat rate and the low LSTs the values from Petrof glacier's foreground fit the model very closely.

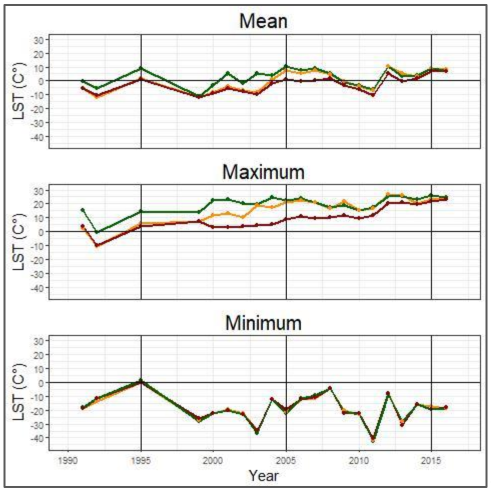


(a)

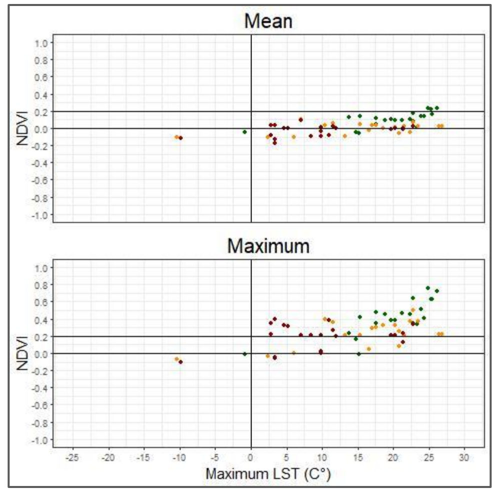


(b)

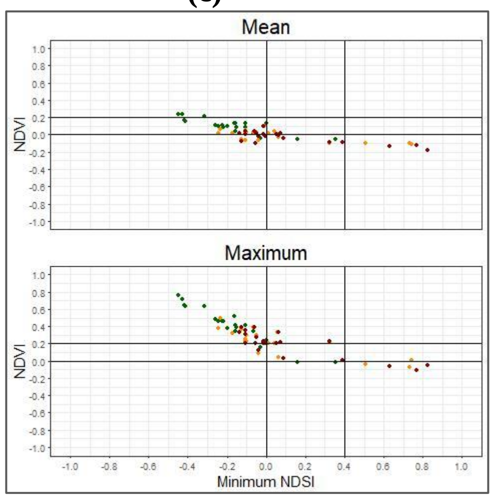
Figure 17: Results of Petrof Foreground.
(a) NDVI (b) NDSI (c) LST
(d) NDVI vs. Maximum LST (e) NDVI vs. Minimum NDSI
Continued on following page



(c)



(d)



(e)

Figure 17 continued

Yalik Glacier

Between 1985 and 2015, Yalik Glacier had the fastest annual retreat rate of all eight glaciers in this study at 51.32 meters per year, 29% faster than the second fastest: Killey glacier. With 71 meters lost per year between 1995 and 2005, Lowell glacier experienced the fastest recession rate tracked by this study. The other two decades saw 52 and 31 meters lost per year respectively. The Yalik glacier tongue flows southward. The western portion flows into a lake while the eastern portion hit land. Being a part of GYGC puts Yalik at a lower elevation than the glaciers in HI. With an average foreground elevation of 846.3 meters, Yalik glacier is the second lowest in elevation, following Petrof (Gesch et al. 2002).

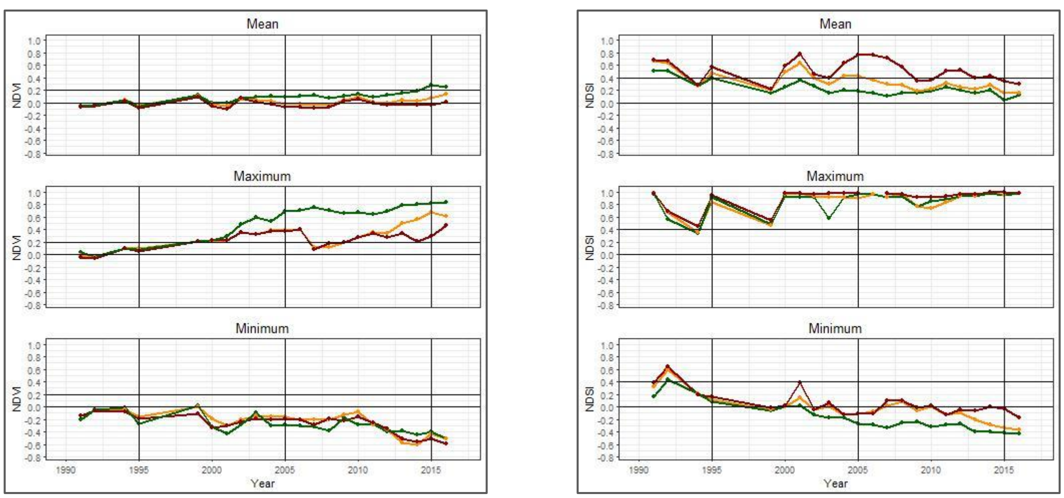
The Yalik glacier foreground has one of the largest differences between maximum and minimum NDVI in the last decade of this study. While the minimum NDVI of most glaciers in this study stays constant through the duration of this study, the values for Yalik glacier begin to decrease near 2010 (See Figure 18). Not only is the minimum NDVI in decline during the final years but the maximum NDVI increases throughout the entirety of this study. While the maximum NDVI of each region always has a positive vegetative response post deglaciation only two years (2015, 2016) of the oldest deglaciated region have this same response.

The mean NDSI shows a steady decline after each region deglaciates. This decline likely aided the maximum NDVI growth. Minimum NDSI of the Yalik foreground is in decline over all 25 years in the study but is below zero after 1995 for all three regions (See Figure 18). Like Petrof, Yalik glacier's LST is lower than the glaciers in HI. Both the average and maximum NDVI of Yalik are lower than expected. All three regions had a large drop in temperature over the 2011 year (See Figure 18). This may be caused by late or early annual snow. The lower temperatures potentially played a large role in the low mean and minimum NDVI response.

The maximum LST and maximum NDVI chart show a clear trend between the two longer deglaciated regions that while the maximum temperature rose, so did the maximum NDVI (See Figure 18). The most recently deglaciated region does not follow this trend.

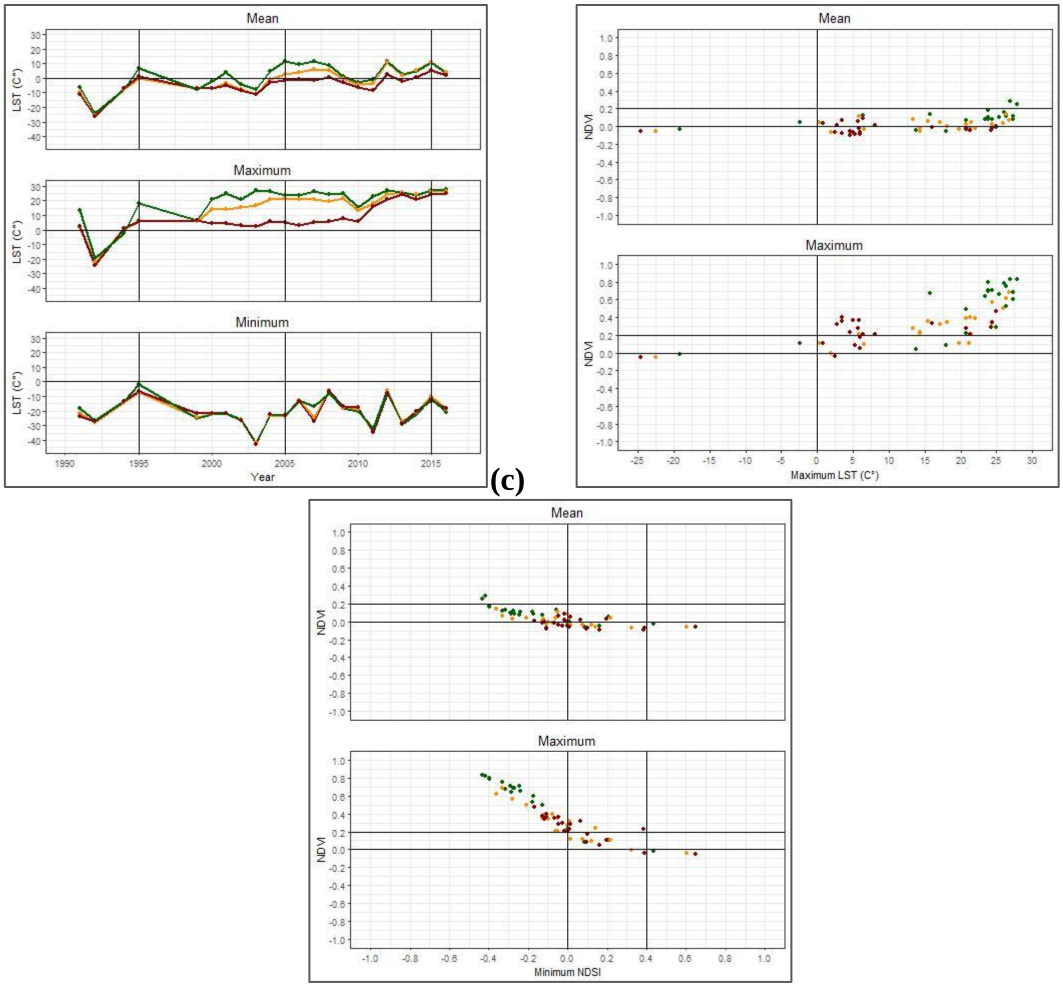
Within this region, the range of NDVI values expressed fall between 0 and 10°C with no discernable pattern. This is unlike the NDVI and minimum NDSI response. The maximum NDVI response to changes in minimum NDSI aligns with the expected model (See Figure 18). As the minimum NDSI decreases, even well below zero the maximum NDVI continues to increase.

Yalik glacier's 709.6 meters of melt between 1995 and 2005 had a lasting effect over the foreground. The oldest deglaciated region had its largest change in maximum NDVI between 2001 and 2002. These years match the second region's largest drop in mean NDSI. There is a possibility that the retreat rate of one region has a strong effect on the vegetation growth of the regions before it.



(a) **(b)**

Figure 18: Results of Yalik Foreground.
(a) NDVI (b) NDSI (c) LST
(d) NDVI vs. Maximum LST (e) NDVI vs. Minimum NDSI
Continued on following page



(c) (d)

(e)

Figure 18 continued

Killey Glacier

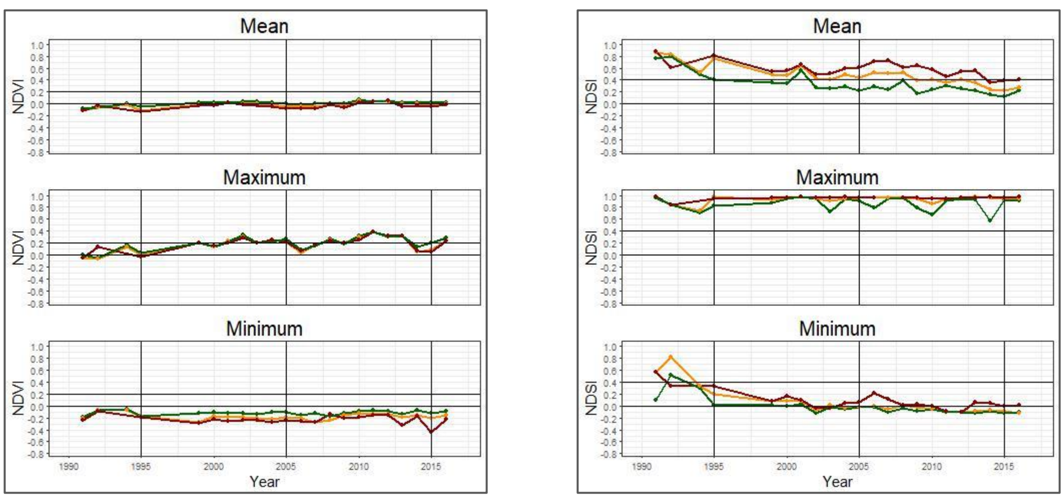
Of the glaciers studied on the Kenai Peninsula, Killey is the highest in elevation. With a foreground averaging 887.7 meters in elevation (Gesch et al. 2002). Killey glacier possess an abnormal retreat pattern. Its exceptionally fast retreat rate in 1985 cause the center of Killey's terminus to retreat faster than either the sides taking the glacier from a convex curve in 1985 to a concave curve in 1995. This concave curve persisted through the following two decades even though the high retreat rate did not. After having only 23 meters of retreat per year from 1950 to 1985, Killey glacier sped up to, 59 meters lost each year for the following 10 years. The glacier eventually slowed back down to 31 and 29 meters per year covered over the next two decades respectively.

The high elevation of Killey glacier places it in an ecotone above the tree line. Because of this Killey is not predicted to gain much vegetation within the 25-year study period. The highest mean NDVI response received over the Killey foreground was from the longest deglaciated region in 2010 with a value of 0.07 (See Figure 19). According to the NDVI response, the Killey foreground is a barren land. Maximum NDVI near Killey glacier have responses that resemble potential vegetation but very few are high enough to be certain vegetation is present.

The NDSI of Killey glacier's two most recently deglaciated regions have average values that are often above the 0.4 threshold for snow/ice cover (See Figure 19). This temporary rise in NDSI values may be the result of glacial advance between years. For the years where NDSI had a reading of snow/ice cover, the average LST had a reading of freezing temperatures (See Figure 19). The cold air and potential summer snow of Killey glacier play into the low NDVI response from the foreground. There is a LST drop for all three regions in 2011, the land surface was potentially snow covered over the summer of 2011.

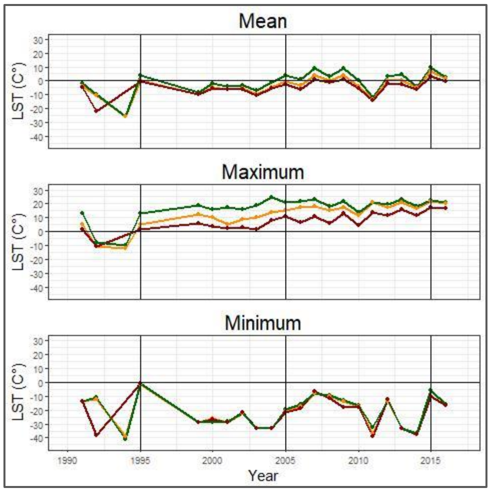
In comparison between the maximum LST and maximum NDVI, there is no discernable trend (See Figure 19). Between the three regions, separations can be made but between the points as a whole, there is no resemblance of the trends that were identified in any of the previous glaciers. Average NDVI and maximum LST have more of a trend but it matches a line saying that the temperature does not matter the vegetation values will be low. The high elevation of Killey glacier may have prevented any vegetation from encroaching quite like the way it does at lower elevations.

Minimum NDSI and NDVI in the Killey foreground have a recognizable pattern (See Figure 19). This pattern roughly matches the traditional NDVI vs. NDSI pattern that is identified with previous papers (Jeong et al. 2013). Although snow and ice have melted from the foreground, Killey glacier's elevation has prevented vegetation from reaching it. The elevation of Killey glacier is a strong impact in the vegetation growth than the rate of recession.

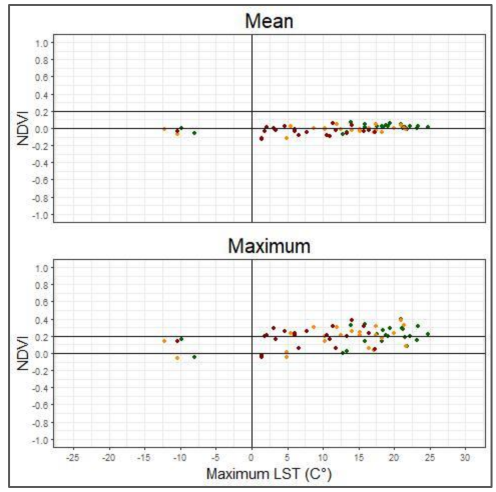


(a) **(b)**

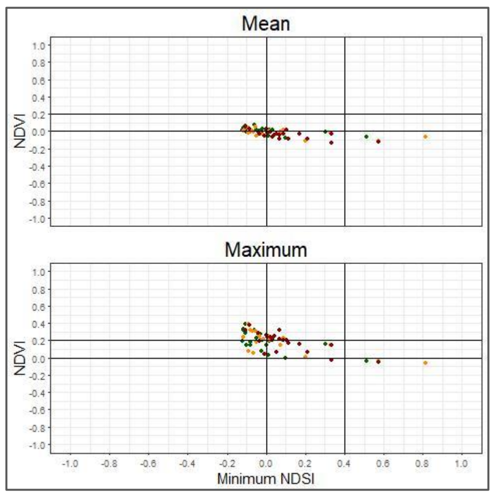
Figure 19: Results of Killey Foreground.
(a) NDVI (b) NDSI (c) LST
(d) NDVI vs. Maximum LST (e) NDVI vs. Minimum NDSI



(c)



(d)



(e)

Figure 19 continued

Kachemak Glacier

Kachemak is the second slowest receding glacier in this study from 1950 to 2015, losing only 794 meters of ice in the last decade and double that since 1950 (Gesch et al. 2002). The melt pattern of Kachemak glacier plays a major role in the ease of vegetative succession. There is a disagreement between the glacier boundary in this study and the GLIMS 2005 boundary for this glacier (See Figure 20). Kachemak's center appears to recede faster than the sides leading to a concave shape in the middle, like Killey glacier in 1995 - 2015. After averaging 23 meters of retreat per year from 1950 to 1985 Kachemak's pace sped up then slowed over the following three decades with rates of 33, 25, and 22 meters per year. Kachemak is the second highest glacier in elevation of this study. With the study area for this glacier averaging 723 meters the elevation has as important of a role as it does with Killey glacier.

The NDVI of Kachemak glacier is constant and low through all three deglaciation zones. The highest average and maximum NDVI values read over this 25-year period are 0.098 and 0.40 respectively (See Figure 20). Kachemak glacier has the lowest maximum NDVI value of any glacier in this study. With respect to NDVI, the three zones do not differentiate from each other at any point. The high elevation and melt pattern of Kachemak are two of the most likely reasons this is happening.

Unlike much of the other glaciers, this newly barren soil remains cold by the ice on three of its four sides. For all three regions of the Kachemak glacier foreground, the NDSI stayed above the snow/ice threshold except for one year, 2003 (See Figure 20). In 2003 the average NDSI of the three deglaciated regions fell below 0.4 regardless of whether it was registered as deglaciated as of yet. The minimum NDSI of Kachemak glacier is similar to values from other, lower elevation glaciers. This value even has various peaks and that extend higher than other glacier's minimum NDSI values.

While the longest deglaciated regions of other glaciers in this study had little trouble sustaining a mean temperature above 0°C after 2005, Kachemak's mean temperature in that region is above freezing for only five of the years in this study. With the mean temperature of Kachemak's constantly near or below freezing there is little reason to question why the mean NDSI stays above 0.4 and the NDVI never reaches 0.1 (See Figure 20). The maximum temperature on the other hand, while low, is consistent with what was expected for slower retreating glaciers in this study. The mean and minimum temperatures for Kachemak glacier do not change between the regions and rarely rise above freezing temperatures.

Much like Killey glacier, the maximum LST and NDVI graphs have a low correlation between them making it hard to identify what is going to happen at any given temperature (See Figure 20). Kachemak is also the only glacier where the three deglaciated regions all overlap each other in NDVI and LST response. The minimum NDSI and NDVI graphs show a similar overlapping between the regions as well. Because the NDVI and NDSI of each region were so close to each other, there is little way to identify what the change is between the regions.

Kachemak glacier is high in elevation and has an abnormal melt pattern. These two features make Kachemak it difficult for ice to fully melt in the foreground but vegetation to grow as well. When the NDVI, NDSI, and LST are compared between the deglaciated zones, there is little variation. This is representative of slow retreat and little encroachment of vegetation.

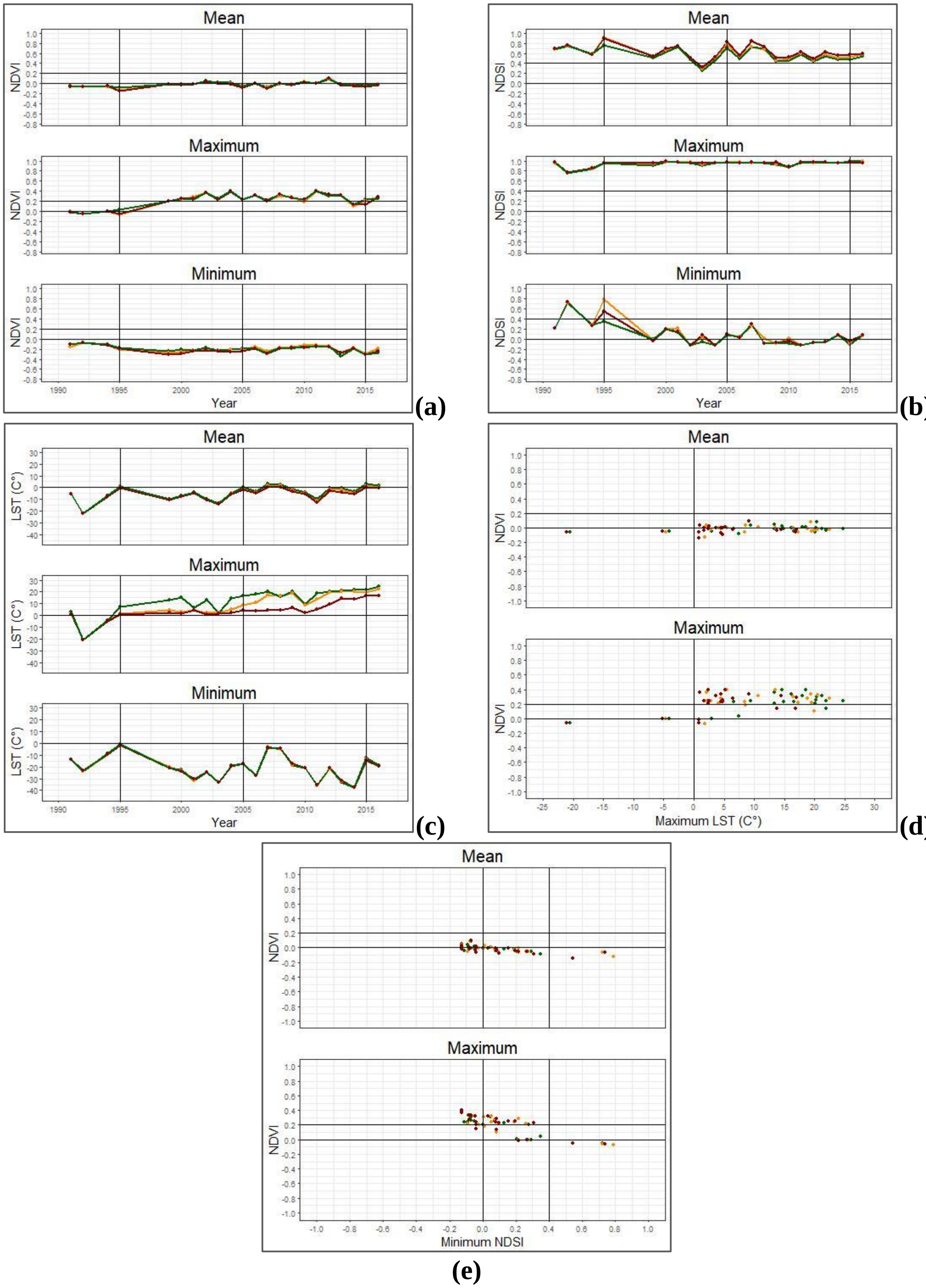


Figure 20: Results of Kachemak Foreground.
(a) NDVI (b) NDSI (c) LST
(d) NDVI vs. Maximum LST (e) NDVI vs. Minimum NDSI

Lowell Glacier

Lowell glacier is the northernmost glacier in this study. Its foreground averages 670 meters in elevation, ranging from 589 to 769 meters (Gesch et al. 2002). Lowell's location on the northern side of HI places it near a hiking trail starting from the Exit Glacier Nature Center. This hiking trail brings people and potentially debris to Lowell glacier potentially impacting the albedo. From 1950 to 1985, Lowell glacier receded at a rate of 21 meters per year. However, for the following three decades Lowell's retreat rate is 24, 35, and 41 meters per year. Over the last 30 years, Lowell lost almost a kilometer and the increasing retreat rate will lead to missing more over decades to come.

The average summer NDVI of Lowell glacier's foreground did not surpass the 0.2 threshold over the 25-year period. The nearest achieved was the final two years in the longest deglaciated range (See Figure 21). The maximum NDVI values of this range have been above the 0.2 value since deglaciation occurred. With the highest maximum NDVI value in this study, Lowell glacier's longest deglaciated region has strong signs of early vegetation cover. Even though the earliest deglaciated range has a peak value of 0.84, the other two regions have peak values of 0.36 and 0.34 respectively. The maximum NDVI values of these two regions do not have a difference greater than 0.1 until 2015.

The maximum NDVI response between the three deglaciated regions are reflected in the minimum NDSI. The minimum NDSI of the longest deglaciated region is significantly lower than the deglaciation of the other two layers that do not have a difference greater than 0.1 until 2015 (See Figure 21). The increasing minimum NDSI of

Lowell glacier's most recently deglaciated region in 2015 and 2016 also reflects the lower maximum NDVI in those years as well. The mean NDSI and mean NDVI have a similar relationship. The values of the two indices have evenly spaced changes between the three regions.

The mean LST of Lowell's foreground followed a similar spacing pattern between the three regions after the second deglaciated region is officially deglaciated. The maximum LST of the longest deglaciated region rises above 20°C five years post deglaciation and by 2016, the other two regions have risen there as well (See Figure 21). The rising maximum LST in all three regions paints a picture that explains why the retreat rate increased over the decades. The three LSTs show a trend where the next decade of melt will have a faster retreat rate than measured by this study.

The NDVI versus maximum LST charts have two varying trends. The trends are similar yet follow different slopes. While the average NDVI versus maximum LST chart has a weak relationship between the two the maximum NDVI has a strong relationship (See Figure 21). The two earlier deglaciated regions have similar increasing patterns between the mean and maximum NDVI charts. Because it spends most of the study glaciated, the mean NDVI and maximum LST show little relation to one another. This is different from the NDVI versus NDSI charts for Lowell glacier (See Figure 21). Plotted against the minimum NDSI, the most recently deglaciated region has much overlap with the region deglaciated before it. While the 1985-1995 deglaciated region has a separate and distinct NDVI versus minimum NDSI relation compared to other two.

Lowell glacier’s recession rate is accelerating by the decade. This accelerated recession is causing the foreground to behave as the expected fast retreating glaciers. Lowell glacier is over double the elevation and less than 10 kilometers away from Exit glacier. Although Lowell is so close to Exit and higher in elevation, the NDVI response in the Lowell foreground is rising while the area of Exit is relatively barren.

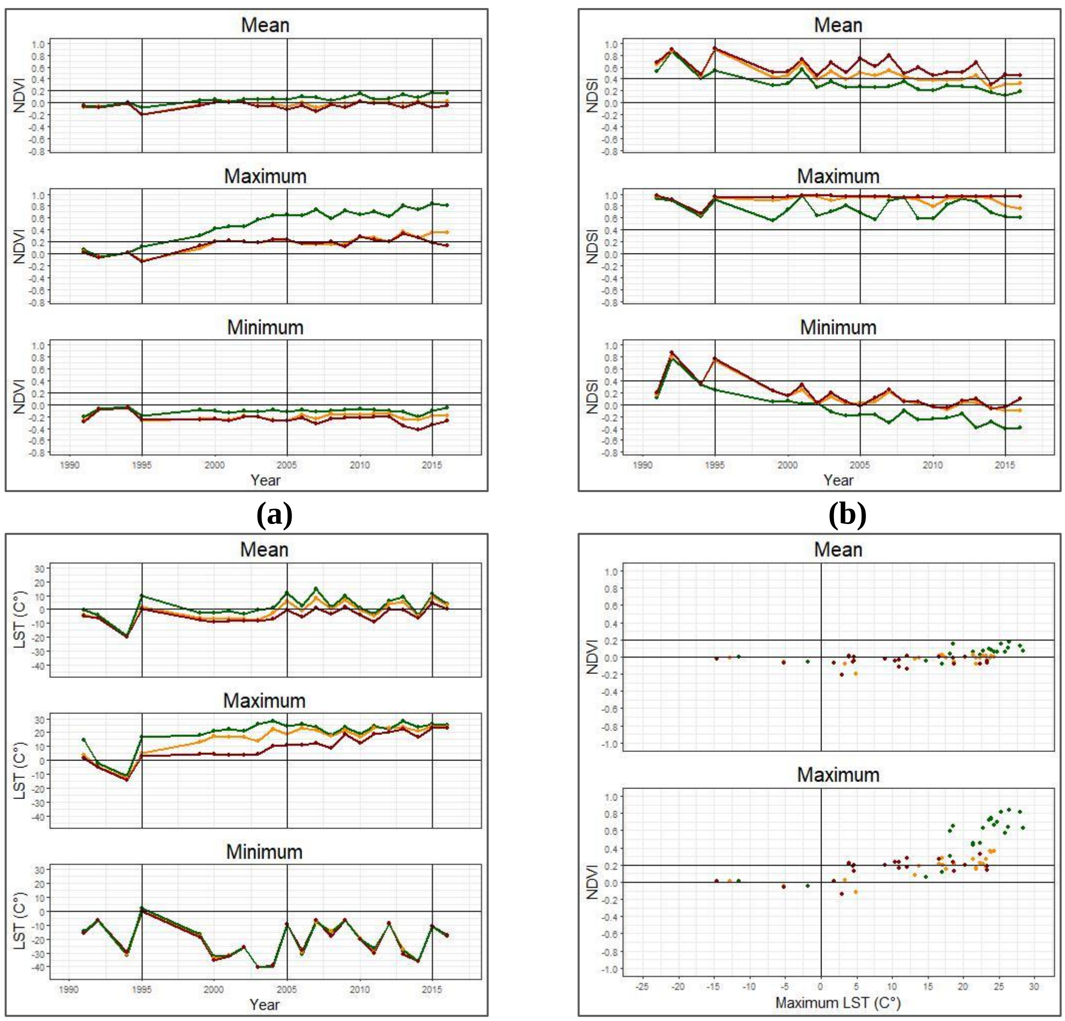
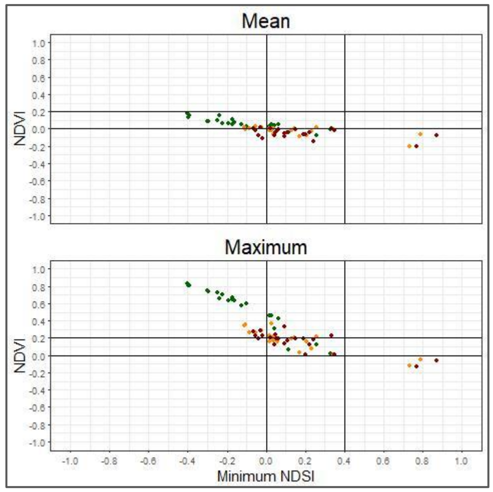


Figure 21: Results of Lowell Foreground.
(a) NDVI (b) NDSI (c) LST
(d) NDVI vs. Maximum LST (e) NDVI vs. Minimum NDSI



(e)

Figure 21 continued

Exit Glacier

Exit glacier has the most foot traffic and research of any glacier in the Kenai Peninsula. The people of KEFJ have even constructed an Exit glacier center two kilometers away from the current terminus. Exit glacier is also special because it has the most human interaction of any glacier in the Kenai Peninsula. Visitors to Kenai Fjords National Park are able to drive the two lane Exit Glacier Road close to the face of Exit glacier itself. This high level of human interaction and ease of accessibility is one of the reasons that Exit glacier is one of the most studied in southern Alaska.

Exit glacier's foreground averages 274.3 meters in elevation between the three deglaciation zones (Gesch et al. 2002). With 941 meters of total retreat between 1950 and 2015, Exit glacier has retreated the least of any glacier observed in this study. Between 1950 and 1985 there was 14 meters of retreat measured per year. From 1985 to 1995, Exit had the lowest annual retreat rate measured in this study with 3 meters lost per year. The following decade for Exit glacier had the second lowest retreat rate measured in this study with 12 meters per year. This retreat is so low largely because the glacier advanced 7 meters from 2000 to 2005 (Giffen et al. 2014). Following this 5-year glacial advance, Exit glacier retreated 306 meters over the next ten years. This is the fastest annual retreat measured for Exit glacier over the course of this study. Unlike the other glaciers in this study, Exit glacier's foreground is a silt flat are. The vegetation has a hard time growing and at times of high melt, there are floods and the foreground temporarily becomes a lake.

The NDVI response of the Exit glacier foreground is low. The highest mean value is 0.08. This occurs in the second deglaciated region in 2010, five year after the region was recognized as deglaciated (See Figure 22). The 26 meters that separate the 1985 and 1995 termini causes little difference between the two earliest deglaciated regions. The changes between them are not recognizable in the mean NDVI but the maximum values do have a change. After 2011, the oldest deglaciated region's maximum values begin to separate from the two latter regions. The higher retreat rate measured between 2005 and 2015 coincide with the sharp rise in maximum NDVI value between 2011 and 2013.

Much like the NDVI, Exit glacier's NDSI are near each other in value throughout the 25-year study period. A rise in the mean NDSI between 2000 and 2005 shows where the glacier advanced between those years. Unlike most of the other glaciers in this study, the maximum NDSI decreases later in the study. As the decadal retreat rate rises the maximum NDSI tappers off. Exit glacier is the only glacier in this study where all three regions have NDSI minimums below 0.4 for the entirety of the study (See Figure 22). The highest minimum NDSI value is 0.30 and was reached in 1994 by the most recently deglaciated region. The low NDSI does not align with the low NDVI nor the expectations of a slow retreating glacier. The land surface type itself may be the general cause of this.

Exit glacier also has low land surface temperature. Over the course of this study, the mean LST never surpasses the 15°C mark in any region (See Figure 22). Moreover, much like the NDVI and NDSI the mean LST between the three regions is similar. There is rarely more than 1.5°C difference between the mean LST of the three regions. Although the mean LST never surpasses 15°C the maximum LST measured is the highest in this study at 27.85°C. The maximum LST continually increases from 1999 to 2016.

The low difference in NDVI, NDSI, and LST between the three regions makes each of the regions hard to discern. As the slowest retreating glacier in this study, there was an expectation that the vegetative succession difference would be minimal between the regions. This expectation was accurately achieved. The minimum NDSI and maximum LST charts created in this lab further show how similar the three deglaciated zones are for the slowest retreating glacier in this study (See Figure 22).

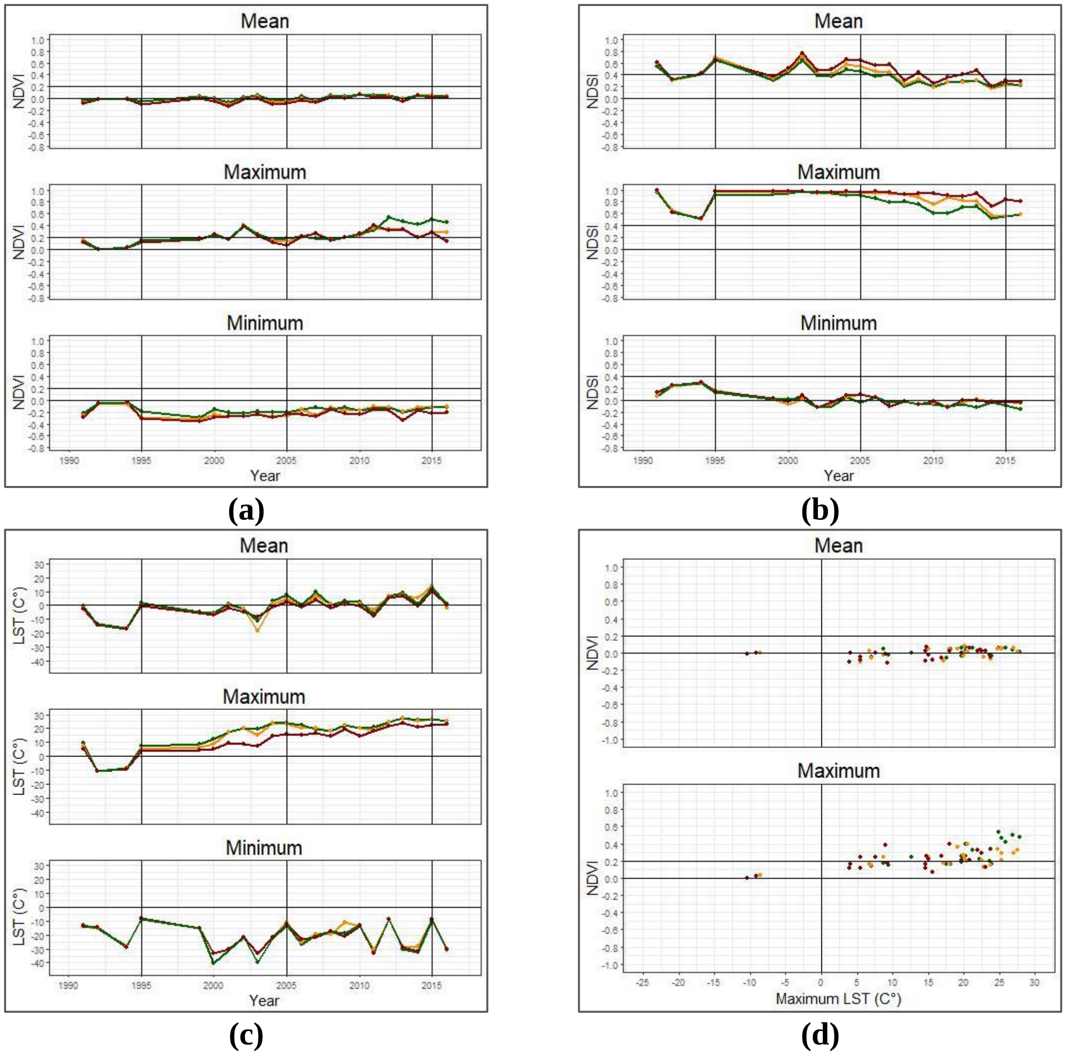
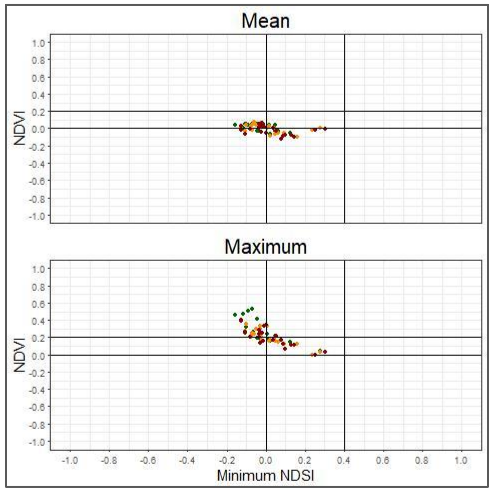


Figure 22: Results of Exit Foreground.
(a) NDVI (b) NDSI (c) LST
(d) NDVI vs. Maximum LST (e) NDVI vs. Minimum NDSI
Continued on following page



(e)
Figure 22 continued

Summary of Results

In this study, data collection begins in 1991 before any of the study regions are fully deglaciated. Over the following 25 years, data was collected through Landsat images to track glacial recession, vegetation growth, and land temperature changes. An NDVI response of more than 0.2 is considered a reading of active vegetation (Klein et al. 1998). Of the eight glacial foregrounds observed in this study, three achieved mean NDVI higher than the threshold (See Table 05). Each are considered fast retreating glaciers. Chernof, the second fastest retreating glacier from 1950 to 1985, only had a peak average NDVI value of 0.083. A key difference between Chernof and the other three fast retreating glaciers is elevation. Chernof glacier's foreground is over 700 meters asl while Dinglestadt, the fastest retreating glacier at 500 meters asl (See Table 02). Therefore elevation plays a major role in NDVI response and vegetation growth rate.

Of all the glaciers in this study, Lowell has the highest NDVI response. From 1950 to 1985, Lowell glacier was the second slowest retreating glacier in this study averaging

21 meters per year. Unlike many of the other glaciers in this study, Lowell has dense vegetation growing in the recently deglaciated foreground. Even the satellite image and land cover classification have the furthest part of Lowell's foreground visibly vegetated (See Figures 16 & 17). Removing Lowell as an anomaly, maximum NDVI is highest for the four fastest retreating glaciers then decreases as the elevation of each glacier increases.

Table 5: Relationship between the measured retreat from 1950 to 1985 and the highest recorded NDVI over the recently deglaciated foreground. *Reprinted from Gifen et al 2014

Glacier Name	Measured Retreat 1950 – 1985 (m/yr)*	Highest Average NDVI	Highest Maximum NDVI	Average Foreground Elevation (m)
Dinglestadt	81	0.278	0.782	486.87
Chernof	39	0.083	0.699	714.78
Petrof	36	0.234	0.756	254.68
Yalik	30	0.288	0.830	257.96
Killey	23	0.072	0.390	722.98
Kachemak	23	0.098	0.401	887.74
Lowell	21	0.174	0.836	669.99
Exit	14	0.077	0.533	274.32

Snow/ice coverage, as measured by NDSI, is directly related to vegetation coverage. The three glaciers with the lowest maximum and average NDVIs correspond to the highest minimum NDSIs (See Tables 05 & 06). Chernof, which has low average NDVI throughout the 25 year study, has a low minimum NDSI unlike the other foregrounds with low NDVI. Although the minimum NDSI of Chernof is low, like the other fast retreating glaciers, the lowest average NDSI is the second highest of all eight glaciers. The different reactions from the mean and minimum NDSI are potentially caused by the higher elevation of Chernof glacier. The NDSI of the low elevation, near-coastal glaciers in GYGC further enforce the elevation to NDSI relationship with their extremely low values. Retreat rate affects NDSI but temperature and elevation also have an effect on the persistence of snow/ice coverage into the summer months.

Table 6: Relationship between the measured retreat from 1950 to 1985 and the lowest recorded NDSI over the recently deglaciated foreground
***Reprinted from Gifen et al 2014**

Glacier Name	Measured Retreat 1950 – 1985 (m/yr)*	Lowest Average NDSI	Lowest Minimum NDSI	Average Foreground Elevation (m)
Dinglestadt	81	0.113	-0.332	486.87
Chernof	39	0.202	-0.326	714.78
Petrof	36	0.004	-0.446	254.68
Yalik	30	0.048	-0.430	257.96
Killey	23	0.116	-0.122	722.98
Kachemak	23	0.255	-0.127	887.74
Lowell	21	0.129	-0.402	669.99
Exit	14	0.165	-0.159	274.32

The role of elevation is also evident in terms of temperature and snow/ice coverage. Killey and Kachemak's highest mean and maximum LST are the lowest of any glaciers in this study (See Table 07). It is no coincidence that the low temperatures align with two slow retreating glaciers at the highest altitude collected in this study. Aside from the elevation of the foregrounds, LST does not exhibit direct relations with the vegetation or snow/ice coverage.

Table 7: Relationship between the measured retreat from 1950 to 1985 and the highest recorded LST over the recently deglaciated foreground
***Reprinted from Gifen et al 2014**

Glacier Name	Measured Retreat 1950 – 1985 (m/yr)*	Highest Average LST	Highest Maximum LST	Average Foreground Elevation (m)
Dinglestadt	81	15.356	26.417	486.87
Chernof	39	13.269	28.106	714.78
Petrof	36	10.513	26.861	254.68
Yalik	30	11.852	27.845	257.96
Killey	23	9.513	24.806	722.98
Kachemak	23	3.337	24.806	887.74
Lowell	21	14.55	28.334	669.99
Exit	14	14.302	27.845	274.32

NDVI in the glacial foregrounds has a higher correlation to the NDSI than LST or elevation. Vegetation growth does not require high temperatures or low elevation but it does require the absence of snow/ice. Although it only represents the peak vegetative output and not the general response throughout the season, maximum NDVI is more directly related to the NDSI and LST than average NDVI.

CHAPTER IV

DISCUSSION

How does NDVI of recently deglaciated areas relate to glacial retreat rates on the Kenai Peninsula?

From 1985 to 2015, the eight glaciers have total retreats ranging from 451 meters (Exit glacier) to 1,540 meters (Yalik glacier) (See Table 02). These major differences in retreat can be attributed to differences in environment surrounding each glacier. The expected NDVI change over 25 years for the faster retreating glaciers is both large and swift. For a fast retreating glacier, the region deglaciated as of 1995 was expected to have a positive vegetative response, as captured by increasing NDVI, within the following 10 to 15 years. Slower retreating glaciers were expected to behave much differently with their earliest deglaciated region experiencing only a small vegetative response in NDVI within the following 15 to 20 years. These expected patterns were indeed found. While retreat rate was found to be the key driver in succession of glacial foregrounds, LST, elevation, and neighboring vegetation also exhibited large effects. The following sections summarize this study's major findings.

Maximum NDVI has a higher correlation with NDSI and LST than mean or minimum NDVI

Maximum summer NDVI is representative of the peak vegetative response of a given region. The peak vegetative response most likely will happen as the snow/ice coverage approaches its minimum and the LST reaches its warmest temperatures. Due to how vegetation responds to the presence of snow, ice, or varying temperatures the mean and minimum NDVI of each year were found to be not as strongly related to NDSI or LST as maximum NDVI.

Maximum NDVI has its strongest relationships with minimum NDSI and maximum average LST annually. These best fitting relationships are assumed to happen on or near the same time during the year. The time period experiencing the NDVI of the summer would also have the least snow or ice coverage, or minimum NDSI. One the other hand, the time period of maximum LST, does not align with maximum NDVI over each respective summer. Instead, average LST and maximum NDVI are closer in relation. There are many reasons that this may be the case. Primarily, the warmest date of each summer may not necessarily occur when NDVI is at its peak but LST steadily rises throughout the summer so even though LST may peak early the mean trend is better aligned with NDVI.

Annual summer NDVI increases more quickly for faster retreating glaciers

The lowest maximum NDVI for each of the longer deglaciated foregrounds are between -0.053 and 0. With the exclusion of Lowell glacier, the slower retreating glaciers (1950 – 1986 retreat rate < 30 m/yr) average a maximum NDVI of 0.473 (and 0.575 with Lowell). The faster retreating glaciers (1950 – 1986 retreat rate > 30 m/yr) have an average maximum NDVI of 0.781. All glaciers started the study with a maximum NDVI between -0.053 and 0. Over the following 26 years the faster retreating glaciers experience a maximum NDVI response that is 165% higher than the slower retreating glaciers (136% including Lowell).

The importance of retreat rate on maximum NDVI is most evident in the regions deglaciated between 1995 and 2005 (See Figure 23). This region, for all eight fast-retreating glaciers, is recognized as officially deglaciated in 2005. Due to the nature of this study, there are only eleven years after deglaciation for the vegetation to establish. Within these eleven years, the faster retreating glaciers had a quicker NDVI increase inferring faster vegetation growth, than slower retreating glaciers.

Ranking the glaciers based on their highest maximum NDVI observed over the 25 years, the fast retreating glaciers are ranked two through five (See Table 05). While Lowell glacier foreground has the highest measured NDVI of this study it experienced the second lowest annual retreat rate. While its average retreat rate was slow over the following three decades it experienced a 196% increase in retreat rate over the initial measured rate. Excluding absolute rate of retreat, Lowell glacier has similar characteristics to other fast retreating glaciers in this study. The LST of Lowell’s foreground is double that of both Kachemak and Killey glaciers which are the two highest elevation glaciers in this study and have different foreground vegetation. This points to the fact that elevation differences and LST while not the major factors in NDVI increase are important contributing factors.

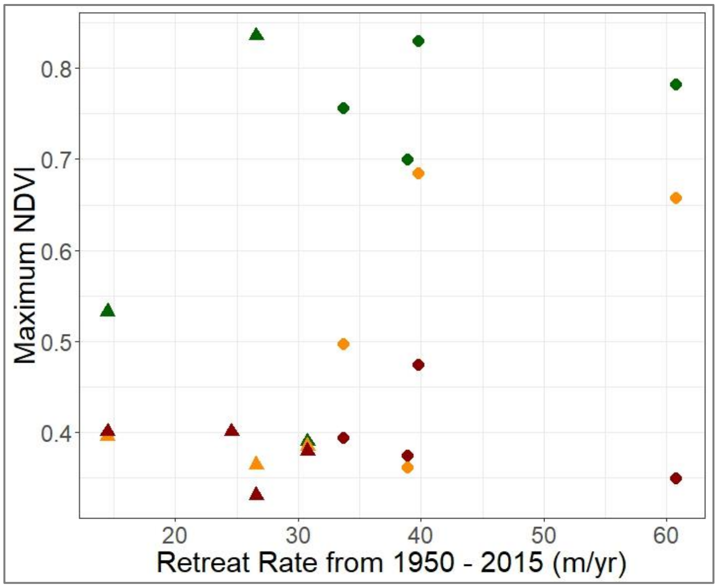


Figure 23: Maximum NDVI of all three regions in the foreground of all eight glaciers (Triangle: Slower retreating glaciers. Circle: Faster retreating glaciers)

Although they are similar in retreat rate and location on the peninsula, a major differences between Exit and Lowell glacier is location of vegetation near their foreground. The foreground of Exit glacier is a riverbed and the neighboring vegetation is located on the slopes above the riverbed. This land cover difference impacts vegetation growth in the Lowell foreground. Lowell's closest vegetation is identified as Alder, like Exit, but grows on the valley floor rather than the hillslope. Using retreat rate to identify succession in glacial foregrounds may be done so long as LST, elevation, and the expected vegetation are also taken into account.

Maximum NDVI and minimum NDSI are negatively correlated for faster retreating glaciers

Annual maximum NDVI represents the yearly peak vegetation of a given region between 1991 and 2016. The minimum NDSI represents the period of least snow or ice over the study. As snow and ice vacate a region, vegetation is expected to grow as evidenced by an increase in NDVI. Figure 24 below shows that although the ice is receding over the foreground of all eight glaciers, vegetation growth typically occurs at a slower pace for the slower retreating glaciers.

Of the four slow retreating glaciers in this study, two exhibit lower changes in maximum NDVI than the others (Kachemak and Killey). This may be the result of their higher elevation compared to the other glaciers in this study. Exit glacier is the lowest elevated slow retreating glacier one of the lowest elevation glaciers, but receded so slowly over the 30 year study period that there was actually a seven meter advance from 2000 to 2005 (Hall et al. 2005). In general, however faster receding glaciers have a stronger negative correlation between their maximum NDVI and minimum NDSI than slower retreating glaciers.

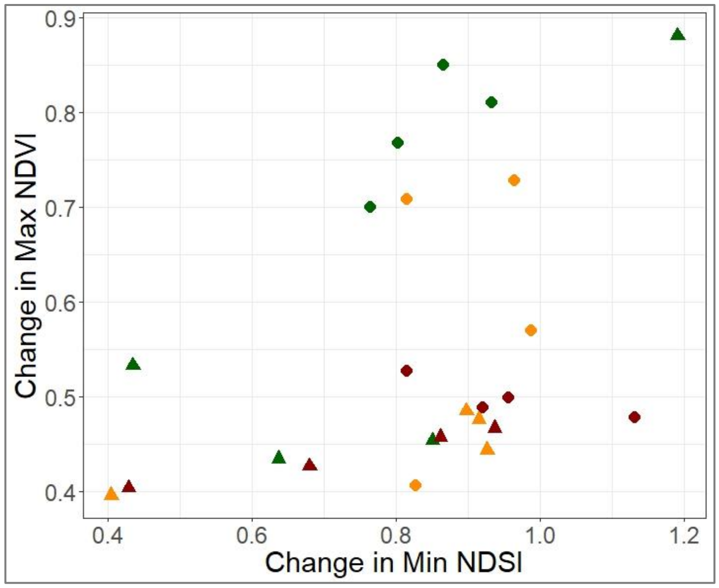


Figure 24: Total change in Maximum NDVI and Minimum NDSI from 1991 to 2016 (Triangle: Slower retreating glaciers. Circle: Faster retreating glaciers)

Little relationship exists between maximum NDVI and maximum LST for slow retreating glaciers

The relationship between maximum NDVI and minimum NDSI is similar to the relation between maximum NDVI and maximum LST. Along the same lines that vegetation grows after snow or ice decreases, summer land surface temperature increase as the snow and ice recedes. Therefore, the foregrounds of faster receding glaciers have a more direct relationship between their maximum NDVI and their average maximum LST over the 1991 to 2016 period (See Figure 25). The slow retreating glacier with the highest maximum NDVI and average maximum LST over the 1991 to 2016 period is Lowell glacier. Even though it acts as an anomaly, Lowell still follows the trend identified.

Most of the studied glaciers experience an average maximum LST within 5°C of one another, but their NDVI varies more widely. There is little correlation between the

NDVI and LST for slower retreating glaciers while the faster retreating glaciers exhibit a much stronger relationship.

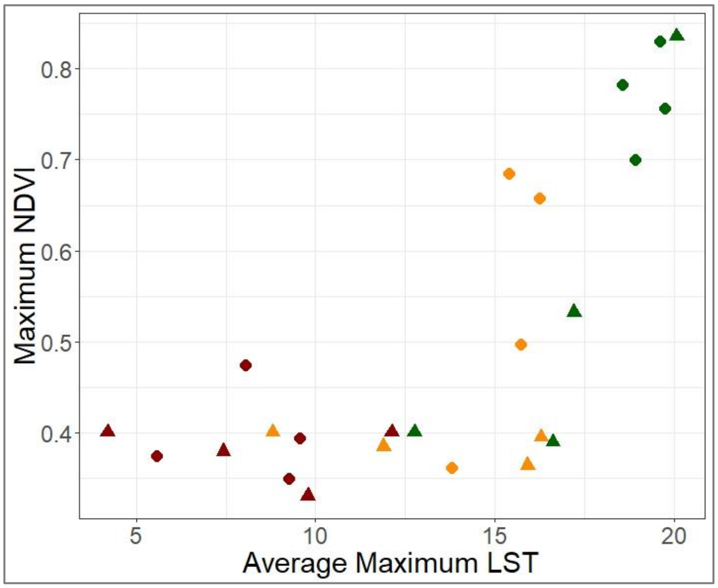


Figure 25: Maximum NDVI vs. Average Maximum LST of all three regions in the foreground of all eight glaciers
(Triangle: Slower retreating glaciers. Circle: Faster retreating glaciers)

LST of faster retreating glaciers tend to be warmer

The average maximum LST from 1991 to 2016 of Lowell and the faster retreating glaciers are higher than the slower retreating glaciers. The slower retreating glaciers with lower NDVI's (Exit, Kachemak and Killey) also have the highest minimum NDSI of the eight glaciers in this study (See Figure 26).

Minimum NDSI reflects the time of least snow or ice coverage over a given region of the foreground. Snow and ice have high albedos so decreasing their spatial extent will lead to lower albedos. These lower albedo regions are expected absorb more energy into the surface thus raising the LST. Higher LST also allow for stronger and longer lasting vegetation growth. This is the link between snow/ice melt, land surface temperatures, and vegetation growth that is identifiable through the Landsat archive.

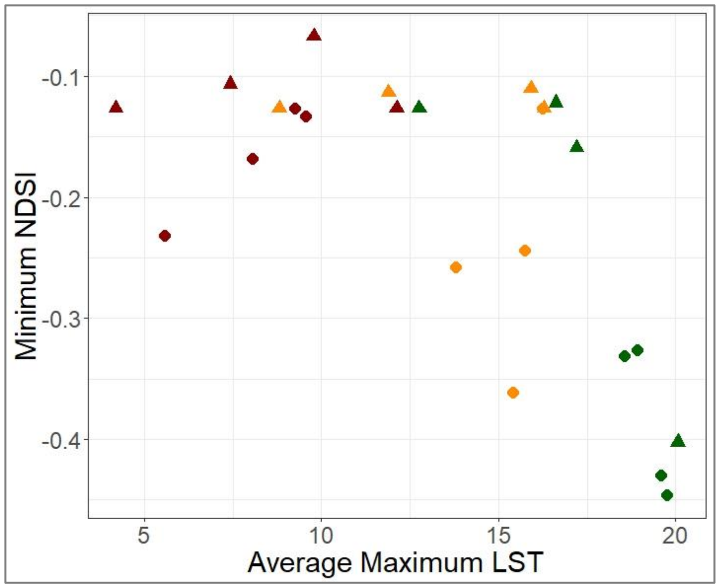


Figure 26: Minimum NDSI vs. Average Maximum LST of all three regions in the foreground of all eight glaciers
(Triangle: Slower retreating glaciers. Circle: Faster retreating glaciers)

Once vegetation is present it grows quickly

The following section uses maximum NDVI to assess the vegetative growth in each glaciers' foreground. Examining the change in maximum NDVI over the 25-year period for each of the glaciers reveals a consistent pattern in NDVI change. In glaciers where the longest deglaciated region has measurable separation in NDVI from the other two more recently deglaciated regions, maximum NDVI in the longest deglaciated area exhibits one or more steep increases. In this study, the intensity of these increases are related to the highest maximum NDVI observed. Figure 71 illustrated the maximum NDVI plots organized from highest to lowest NDVI observed in their foregrounds over the 25-year period (Lowell, Yalik, Dinglestadt, Petrof, Chernof, and Exit). Kachemak and Killey glaciers were omitted because there is little difference in NDVI between the three regions in their foregrounds over the study period (See Figures 08 & 09). The three glaciers on the right side of Figure 27 have average foreground elevations below 300 asl while the three glacial foregrounds on the left side of Figure 27 have average elevations above 450 asl (See Table 02).

After its initial separation in maximum NDVI from the other two regions, the longest deglaciated region experiences a rise to at least 66% of its maximum observed NDVI during the following five to eight years. Quantitatively, there is little linkage between maximum NDVI change in the foregrounds and the other factor examined. Yet, qualitatively, a pattern of succession is identifiable. With the exception of Exit glacier, the previously mentioned step-wise function is visible in the maximum NDVI pattern of each glacier. For example, Dinglestadt has maximum NDVI growth from 2003 to 2006 and 2010 to 2016 with a period of little change in-between (See Figure 27). The trend of the years from 2006 to 2010 in the Dinglestadt foreground occurs near other studied glaciers as well. Some form of this pattern is identifiable in the longest deglaciated portion of five of the eight foregrounds in this study. Additional work needs to be done to understand what specifically happening during this time of little-to-no growth as evidenced by little or no change in NDVI.

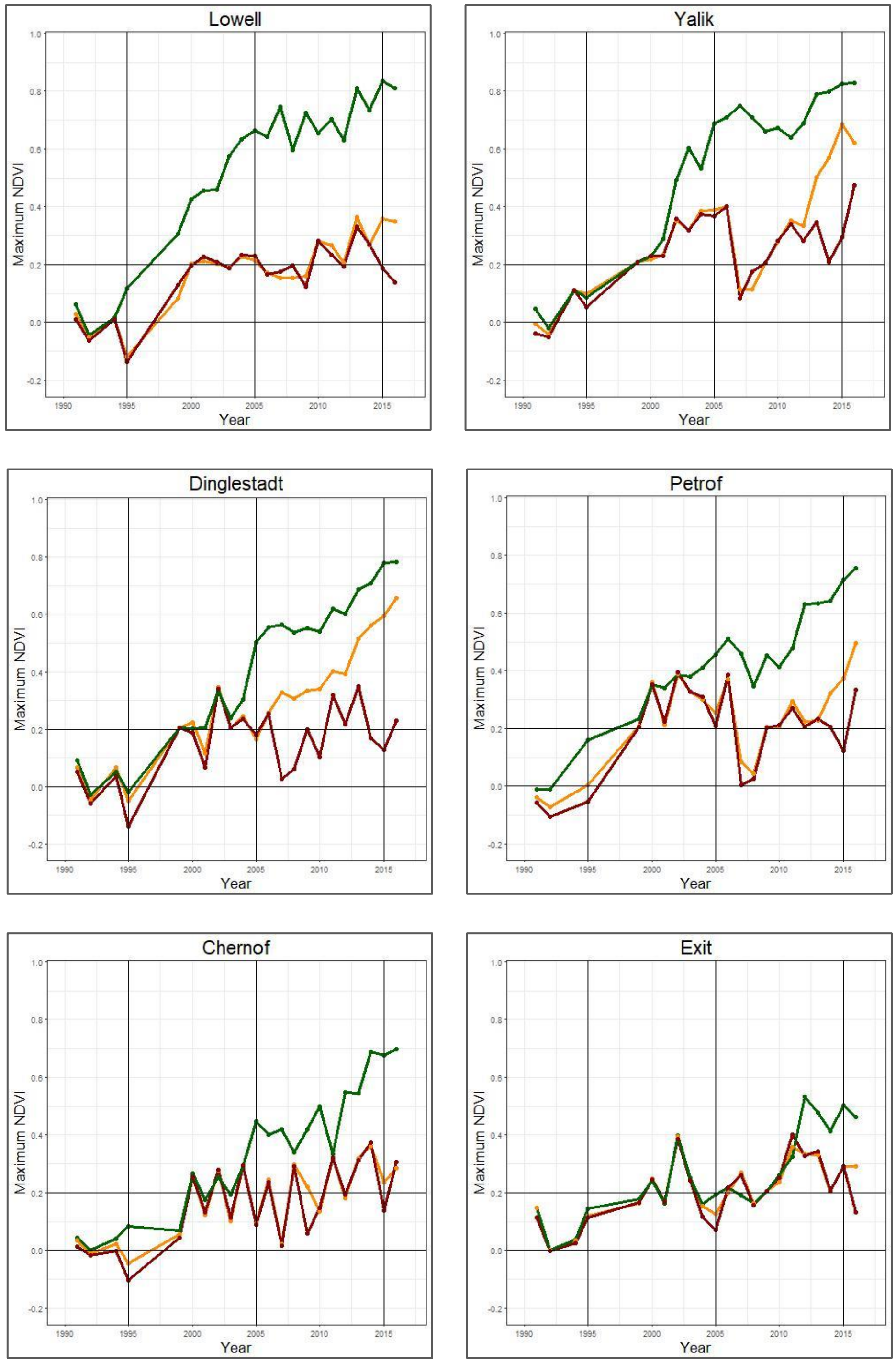


Figure 27: Maximum NDVI plot of each glacier ordered by magnitude of maximum (Kachemak and Killey glaciers omitted due to difference in NDVI between the three deglaciated regions)

Yalik, Dinglestadt and Petrof glaciers also experienced maximum NDVI growth in their second most recently deglaciated region. Yalik and Petrof are two low elevation foregrounds in the GYGC. Their two earliest deglaciated regions both experienced initial increases in NDVI during the same years, 2000 and 2012 respectively. The fact that these two foregrounds experienced the similar increases in NDVI during the same year although they had different retreat rates suggest other factors such as warm coastal air and lower elevation impacted initial growth. These two years of significant NDVI increase align with observed local maximums in LST (See Figures 17 & 18). Likewise, in the higher elevation Dinglestadt foreground, the year where its two regions experienced a growth in maximum NDVI are also the last years those regions expressed average LST below freezing (See Figure 15). Regardless of elevation, LST appears to effect vegetative growth and can lead to large changes in vegetation intensity, as measured by NDVI, over the following few years.

Can primary succession in deglaciated lands be detected using the current US Earth Observing satellites?

Primary succession is the development and growth of biota in previously uninhabited environments. The biota this study observed was various vegetation types over recently deglaciated regions. With the use of three US Earth Observing Satellites, this study monitored land cover change from glacial conditions through barren surfaces then continued to observe the areas as vegetation growth began. Both mean and maximum NDVI values indicate vegetation growth each summer. Using NDVI from Landsat 5, 7, and 8, primary succession is identifiable at a 30-meter scale.

NDVI values greater than 0.2 in this study taken to indicate the presence of vegetation. Using this criteria all glacial foregrounds in this study experienced, vegetation change within the Kenai Peninsula’s barren lands were as observed in the 25-year period using the Landsat satellites. However without annual field research to characterize the vegetation, it is difficult to accurately identify if primary or secondary succession is occurring in the locations identified in this study using satellite observations.

CHAPTER V

CONCLUSIONS

Poleward expansion of vegetation is altering the cryosphere's energy budget and bringing more heat and energy into these regions and potentially leading to vegetation succession. Knowledge of what factors lead to succession in previously ice-covered areas is important for climatic, cryospheric and energy models. Glaciers are responsible for 35 to 50 percent of sea level rise since 1800 and with the feedback loop observed in this study, that number will continue to rise.

Using NASA Earth Observing satellites, both deglaciation and vegetative succession are identifiable over the Kenai Peninsula study site. The Kenai Peninsula is home to two large ice masses, currently in retreat, surrounded by varying vegetation types. The succession identified in deglaciated foregrounds of the Kenai Peninsula has been occurring for decades. As deglaciation is occurring globally, it is expected that deglaciated land worldwide are experiencing succession at carious rates.

Studying the foregrounds of eight glaciers, succession in formerly ice-covered areas of the Kenai Peninsula between 1991 and 2016 was found to follow this pattern. Previously ice-covered regions warmed exposing barren rock and soil. As these regions continued to warm their albedo decreases as the albedo of the barren land is less than that of ice or snow leading to increases in energy absorption. Primary succession then begins to occur eventually providing the soil and nutrients for shrubs and other plants to grow in the region. This process was detailed in this project for eight distinct locations between

1991 and 2016. Succession was measured using NDVI while deglaciation was tracked using NDSI.

Years with higher annual maximum LST measured over the glacial foreground closely matched the years of lowest NDSI as vegetative growth cannot initiate until the region is ice-free thus making temperature and low NDSI the first sign of potential succession. As measured by NDVI, once vegetation became established vegetative growth rates were highly variable between the glacial foregrounds on Kenai Peninsula. Faster retreating glaciers experienced earlier growth than most slower retreating glaciers during the study period.

Both NDSI and NDVI were affected by the maximum LST. The rate of increase of NDVI for recently deglaciated areas exhibits a strong relation to glacier retreat rates in the Kenai Peninsula. Foreground elevation and LST play a lesser role than retreat rate and snow/ice coverage, as measured by NDSI, in vegetation response.

Here retreat rate is identified as a major factor in the greening of recently deglaciated lands. The retreat rate of each glacier is related to the vegetative growth, measured by NDVI, in the deglaciated foregrounds. The faster retreating glaciers exhibit higher vegetative responses, in comparison to the slower retreating glaciers. Lowell glacier was found to be the singular exception. Even between the two glaciers on GYGC, the faster retreating Yalik glacier had a faster increasing and higher NDVI than Petrof. This is significant because these two glaciers are nearly identical in all factors observed in this study except retreat rate. More study is needed to understand to what degree other factors such as LST, elevation, and vegetation type have on vegetation growth.

Future work

Future research would include studying additional glacial foregrounds to understand more about location variability. Additionally, cataloging annual changes of glacier termini and identifying if the patterns of each foreground's NDSI reflects annual terminus change. Using annual changes in termini can also identify what effect the annual retreat has on NDVI and LST. The use of higher resolution images, both spatial and temporal, will increase confidence and accuracy in tracking annual changes.

The atmosphere and weather play a role in vegetative response each year. This research did not address how annual rainfall or seasonal snow cover affected the following year's growth. Having sites closer to weather stations would aide in linking these factors to vegetation growth. Fieldwork to place sensors that measure, not only, the atmosphere but also land surface components could be added to obtain air temperature, rain/snow fall amounts, and LST in addition to those properties captured by Landsat. Future research will aim to gather a deeper understanding of the interconnectedness between deglaciation and succession as well as their role in the climate change feedback loop.

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