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One Hundred Years of Vegetation Succession in the Easton Glacial Foreland, Mount Baker, Washington

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One Hundred Years of Vegetation Succession in the Easton Glacial Foreland, Mount Baker, Washington

By

Katherine Ann Rosa

Accepted in Partial Completion
Of the Requirements for the Degree
Master of Science

Kathleen L. Kitto, Dean of the Graduate School

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MASTER'S THESIS

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Katherine A. Rosa

May 24, 2016
One Hundred Years of Vegetation Succession in the Easton Glacial Foreland, Mount Baker, Washington

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

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Abstract

This research describes stages of primary succession in the Easton glacial foreland on Mount Baker, Washington. The Easton foreland is an alpine landscape displaying the processes of primary succession from barren substrate to a developed forest within 1.95 kilometers and over a short geologic period of approximately one hundred years. Patterns of vegetation succession vary among forelands around the world. In the Easton foreland, vegetation development was measured by percent cover, richness, and species diversity. Environmental variables (distance from glacier (proxy for time), elevation, soil moisture, photosynthetic active radiation (PAR), slope, and aspect) were measured to determine factors influencing vegetation development during primary succession. The main finding from this study is that distance from the Easton glacier is the most significant variable influencing vegetation development, and that the relationship between vegetation cover and distance is non-linear. This indicates a rapid establishment initially after the glacier retreats and a gradual development from about 40-100 years. This suggests a chronosequence is sufficient for explaining vegetation development on a small temporal and spatial scale. Vegetation cover and richness increased through succession, with low values of vegetation richness compared to a neighboring foreland. Diversity remained consistent at a Shannon-Wiener Diversity index value of about 1. The other environmental variables played a smaller role in vegetation development. Only fifteen plant species were found with the most abundant species being: *Lupinus polyphyllus*, *Laetkea pectinata*, *Tsuga mertensiana*. Most notable was the early presence of *Tsuga mertensiana* saplings within 20 years of glacial retreat, suggesting a relationship to the more developed forest on the surrounding moraines that are likely providing a seed-bank for the valley. The findings of this study advance the small but growing field of Cascadian foreland studies and contributes valuable information to the discussion of alpine ecosystems responses under anthropogenic climate change.
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Chapter 1. Introduction

Mountain regions play a key role for humanity through cultural, biological, and economic contributions. Alpine ecosystems provide valuable goods and services to highland and lowland societies through climate regulation, extractive resources, agricultural production, biodiversity, watershed storage, recreational opportunities, and cultural diversity (Körner and Ohsawa, 2005; Gret-Regamey, 2008). These ecosystem services are at risk in the face of anthropogenic climate change (Courbaud et al., 2010).

Alpine and glacier environments are particularly fragile and therefore sensitive to climate change (Meier et al., 2003). The effect of climate change on alpine ecosystems will be directly observed through alterations in vegetation and glaciers, seen through shifts in species distributions (Lenoir, 2008), changes in community composition (Courbaud et al., 2010), and the rate and intensity of glacial retreat (Zemp et al., 2015). Climate predictions for mountainous regions remain uncertain due to limitations of modeling such as coarse spatial resolution, topographic smoothing, and local effects not captured in models (Bach and Price, 2013). Moreover, climate change impacts on alpine vegetation are yet to be fully understood. The interplay between glacial retreat and vegetation development found in glacial forelands link these major indicators of climate change.

Glacial forelands provide excellent opportunities for researching processes of primary succession due to their restricted physical size, severe climatic environment, and the relatively short history of modification by natural processes (Matthews, 1992). Primary succession begins when plants colonize a surface with little to no remnant of biological life following a severe disturbance such as glacier retreat (Walker and del Moral, 2003). Unprecedented glacier decline
has been observed in the field and on satellite images for many glaciers around the world, including Mount Baker (IPCC, 2014). Seventy-five percent of glaciers in the North Cascades are rapidly thinning (Pelto, 2006) and are predicted to continue retreat into the foreseeable future (Pelto, 2010). As a glacier retreats, the process of soil development and plant succession begins on the newly exposed surface. Patterns of vegetation succession vary among glacial forelands around the world; however, there have been few studies documenting the vegetation in the glacial forelands in the Cascade mountain range of North America.

The Easton glacier foreland of Mount Baker, Washington (48°46’38” N, 121°48’48” W) is located approximately 50 kilometers due east of Bellingham, Washington. It exists in an area of west coast maritime climate conditions. Mount Baker is an active stratovolcano and the highest peak in the North Cascade mountain range (3285 meters). Mount Baker is covered with a 38.6 km² ice-cap consisting of ten major glaciers (Pelto & Brown, 2012). All of Mount Baker’s glaciers have been retreating in concert since 1990 as a result of climate variations (Harper, 1993; Pelto, 2013). The Easton glacier is located on the southwest aspect of Mount Baker and has experienced major changes in mass balance over the last century (Pelto, 2015). The Easton glacier foreland is the area directly in front of the Easton glacier terminus and is the location for my study (Figure 1.1). The Easton glacier generally retreated from 1912 to 1956, then re-advanced until 1990, and has retreated since (Harper, 1993; Pelto & Brown, 2012). Overall, the Easton glacier has mostly experienced retreat throughout the last one hundred years, increasing the area of the glacier foreland. Specifically, during 2015, the Easton glacier retreated 40 meters (D. Clark, personal communication, September 2015; Pelto, 2015). This is significant retreat in a
short period of time, confirming the importance of documenting patterns of vegetation as new terrain becomes exposed.

Globally, mountain ecosystems support about one quarter of terrestrial biodiversity (Körner and Ohsawa, 2005). Climate change is interconnected with biodiversity: the timing of vegetation blooms, species migration, and community composition in existence today will be altered under new climates (Behera, et al., 2012). Cold-adapted vegetation communities currently situated at high elevations are likely to disappear while forests expand as a result of climate change (Körner and Ohsawa, 2005). Functioning alpine ecosystems provide invaluable ecosystem services that are worth preserving. Researching primary succession in glacial forelands provides an assessment of the current condition of alpine ecosystems that can be used to predict the effect of climate change on these critical environments.
1.1 Purpose of Research

This research documents the evolution from a barren rock strewn landscape to a fully developed late-successional forest over one hundred years in the Easton glacial foreland on Mount Baker. Stages of primary succession will be described to determine temporal patterns of vegetation establishment and growth following glacier retreat. Environmental variables will be examined to understand the main factors influencing vegetation development. The Easton glacial foreland is a landscape worth investigating due to the significant changes observed and the limited amount of previous research conducted at this site.
Studies of glacial foreland succession have taken place around the world including: Alaska, Kenya, Norway, Switzerland, Iceland (Cooper, 1923, 1939; Mizuno, 2005; Matthews et al., 1987; Vetaas, 1994; Burga et al., 2010; Vilmundardóttir et al., 2015). Together, these studies construct observations of glacial foreland ecosystems around the world, allowing for the amalgamation of findings that assist in understanding factors affecting primary succession within the Easton foreland.

Only a few studies have been conducted on the ecology of glacial forelands on Mount Baker (Jones et al., 2005; Whelan, 2013). Jones et al. (2005) studied patterns in community development at different terrain age classes on the Coleman glacial foreland of Mount Baker (a northwest facing slope). They found scale dependent patterns in diversity of vegetation and stressed the constraints of the dating system used to establish their terrain age classes, emphasizing the need for considering site-specific environmental variables. In 2013, Whelan studied soil development in the Easton foreland. The author found soil development was best indicated by patterns of vegetation and examined certain soil nutrients crucial for plant development: organic matter, carbon content, nitrogen content, carbon/nitrogen ratio, soil pH, and vegetation cover (Whelan, 2013). This study builds on the findings of Jones et al. (2005) and Whelan (2013).

1.2 Research Framework
The geoecological framework adopted in this research is an extension of the widely used chronosequence framework (Matthews and Whittaker, 1987). The chronosquence framework is a spatial sequence in which physical environmental factors other than time are held constant or
controlled (Matthews and Whittaker, 1987). The geoecological framework includes environmental factors in addition to the temporal sequence.

A chronosequence approach to glacial foreland studies provides an appropriate method for temporal analysis of vegetation change, which is the most important factor of succession (Matthews, 1992). With increasing distance from the glacier terminus more time has elapsed for ecosystem development, thus vegetation patterns can be observed through a chronosequence (Matthews, 1992). The chronosequence approach has been applied in this research by using distance from the Easton glacier as a proxy for time. Chronosequences have been applied in foundational studies of glacial foreland vegetation (Cooper, 1923; Crocker, 1959) and was the accepted framework in vegetation ecology, following a reductionist philosophy that vegetation follows a linear trend and eventually reaches a climax community (Clements, 1916). An international effort began in the 1950s and 1960s to study systems ecology. This lead to the modern method of integrating holistic philosophies that consider environmental variables within successional research, making way for adoption of the geoecological framework (Walker and del Moral, 2003). While the importance of the physical environment has long been recognized, until recently there has been reluctance to fully embrace its implications.

The geoecological framework emphasizes the consideration of successional patterns within chronosequences and along environmental gradients of glacial forelands. This framework is defined by two key concepts: (1) biological and physical systems interact within the glacial foreland, and (2) the characteristics of succession and soil development vary broadly in relation to environmental severity (Matthews, 1992). Applying the geoecological framework provides a
temporal analysis of vegetation patterns and refines key environmental factors influencing vegetation development within a glacial foreland.

1.3 Research Questions

This research is anchored by two main purposes: 1) to describe the temporal stages of primary succession and 2) to identify the relationships between micro-site environmental variables and vegetation development. These purposes will be accomplished with two main research questions:

• How do vegetation cover, richness, and species diversity change through succession?

• How are changes in vegetation cover, richness, and species diversity related to environmental variables: distance from glacier, elevation, soil moisture, photosynthetic active radiation (PAR), slope, and aspect?

To answer we conducted field research during the summer of 2015. Randomly selected sites were delineated using a 0.5 square meter quadrat throughout the Easton foreland. Within each quadrat, vascular plants were identified. Vegetation cover, richness, and abundance were measured for each species. Environmental variables were measured within each quadrat using various sensors and tools to quantify distance from glacier, elevation, soil moisture, PAR, slope, and aspect. Alpine plant life is primarily limited by low temperatures, solar radiation, wind or insufficient water availability (Beniston, 2003). The environmental variables measured in this study reflect these factors.

Distance from the Easton glacier was measured to provide a temporal analysis of vegetation change over one hundred years following glacial retreat.
Elevation was chosen as a proxy for air temperature. High-elevation and alpine vegetation has adapted to survive at lower temperatures (Körner, 2003) but are at risk of disappearing under climate change. As the climate warms, cold-adapted species may lose suitable habitat in alpine environments. This adaptation to low temperatures is exhibited differently by each species; thus, elevation is a necessary variable to measure. Within a glacial foreland, elevation is expected to increase with decreasing distance from the glacial terminus. Globally, the general distribution of ecosystems is based on altitudinal zonation (Figure 1.2) although patterns can be site-specific. This research falls within the alpine/sub-alpine zones. Changes in elevation also influence precipitation totals and number of snow-free days, contributing to the short growing season for alpine vegetation (Beniston, 2003).

Slope is an important variable for microclimates as it relates to soil stability. Steeper slopes experience greater erosional activity, rarely allowing soil to develop or plants to establish (Körner, 2003). Vegetation provides a protective role against slope erosion (Beniston, 2003). Slope was measured to understand the limits of steepness upon which vegetation grows in this study area.

Aspect influences vegetation by controlling the amount and duration of solar radiation received by the plants for use during photosynthesis. Changes in micro-site aspect throughout the foreland influence solar intensity on vegetation development. Although the Easton foreland is predominately south-west facing, variation in micro-site aspect measurements was anticipated based on findings from Whelan (2013).

PAR is the fraction of light absorbed by plants and transformed into energy during photosynthesis. It is in the spectral range of 400 to 700 nanometers in wavelengths and is
expressed in micromoles per second per meter squared (LI-COR, 2016). Measuring PAR provides a numeric assessment of the receipt of solar radiation used by the plants. Species of vegetation respond uniquely to differing levels of PAR. For example, shade tolerant plants harvest PAR most efficiently at low light levels, and less efficiently at high light levels (LI-COR, 2016). PAR varies seasonally and throughout the day due to changes in sun angle.

Soil moisture is required for plants to begin their growth cycle once seeds are dispersed on barren substrate. This variable was measured to determine if hydric stress was limiting vegetation development.

Figure 1.2: Zones of vegetation composition based on elevation gradient
This study contributes to the growing field of Cascadian foreland studies by providing temporal analysis of primary succession and determining significant environmental factors influencing vegetation development in the Easton foreland on Mount Baker. More broadly, this study will provide information that can be used in understanding the impacts of climate change on alpine ecosystems.
Chapter 2. Background

Most landscapes of the Pacific Northwest are largely a reflection of their glacial history. During the most recent Holocene epoch period of geologic time, following the Little Ice Age, glaciers have retreated significantly (Mann, 2002) leaving behind evidence of their previous existence. Once ice-covered, this new land is exposed to the biosphere, creating the landscapes of the Pacific Northwest today. While small in spatial scale, these landscapes are likely to grow in size over the coming decades as climate change continues. These changes will provide an analogy to the end of the Pleistocene era when deglaciation affected all of the Puget Sound Lowlands. These changes have been a topic of research for many scholars and remain an area of interest today as glaciers continue to melt. In this chapter, I discuss the progression of influential theories of primary succession and how the ecology of recently deglaciated terrain has advanced successional theory. Then, I discuss the climatic, geologic, pedogenic, vegetative, glacial, and recreational characteristics relevant for vegetation development within the Easton foreland.

2.1 Theories in Primary Succession

Succession is considered the second most important concept in ecology, behind the ecosystem concept (Walker and del Moral, 2003). Ecologists have been seeking to understand the patterns, processes, and changes observed in vegetated landscapes for over a century, yet multiple theories of why succession occurs remain. Just as glacial retreat provides a dramatic visual example of the effects of climate change, primary succession provides visual evidence of vegetation development following disturbances. Primary succession is defined as the gradual colonization and establishment of plant communities on freshly exposed terrain following a disturbance (Molles, 1999). Thus, disturbances are necessary for primary succession as it is the disturbance that creates the substrates upon which new ecosystems can develop. Types of
natural disturbances include events such as volcanic eruptions, earthquakes, floods, landslides, hurricanes, and movement of glaciers. Once a disturbance initiates primary succession, the fascinating transformation of the landscape from a barren substrate to a mature ecosystem begins.

A wide variety of theories explaining mechanisms of primary succession have been presented over the last one hundred years. It is beneficial to revisit the historical progression of successional theories in order to appropriately situate this study within the field of research. At the beginning of the rise of the formal discipline of ecological science in the United States (McIntosh, 1975), Clements (1916) presented a holistic theory to explain the nature of the vegetation community that is a result of succession. His theory is large-scale and focuses on the community level of vegetation. Clements (1916) claimed that succession was driven by six processes: nudation, migration, ecesis, competition, reaction, and stabilization. Nudation is the process where a disturbance occurs, initiating succession. Migration considers life history characteristics of species of vegetation relevant for dispersal mechanisms, such as seed-size. Once the seed migrates to the environment, ecesis plays a role in the species’ ability for establishment and growth in low nutrient conditions. Competition drives out the species whose characteristics are not suitable for the environment. Reaction occurs in the environment itself and is a modification by the present organisms coping with their new neighbors, the vegetation. Lastly, stabilization occurs by the vegetation community reaching its climax state controlled primarily by the climate (summary adapted from Walker and del Moral, 2003). Many of these processes still remain accepted and have shaped understanding of succession greatly by providing a framework within which to place observations of vegetation development.
Clements’ theory was challenged for its deterministic and linear view of the community structure. Gleason (1926) directly refuted the idea of a climax state of a community and instead focused on distributions of individual species along environmental gradients in a reductionist approach. Gleason’s (1926) more individualistic approach stated the community was constructed based on the relationship of coexisting species and the similarities in their requirements for dispersal, growth, and development. One criticism of this approach is that it seemingly does not consider competition and implies that the species do not interact (Walker and del Moral, 2003). Still, Gleason brought to the forefront of ecological studies the idea that communities are not permanent but are continually changing based on species adaptations and competition. His research was validated in 1959 when the Ecological Society of America awarded him the title of “eminent ecologist”. This event steered the field of ecological science to emphasize reductionism and decline the Clementisian concepts (Cain, 1959 as cited in Walker and del Moral, 2003).

Since the 1950’s, ecological studies have been fueled with a Gleasonian emphasis from observational and experimental data on individual species within certain environments (Walker and del Moral, 2003). However, there has yet to be a replacement for Clements’ successional framework. Many modern theories have synthesized the pioneering ideas of both Gleason and Clements within studies of the ecology of deglaciated terrain.

2.2 Theories of Succession from the Ecology of Deglaciated Terrain

The ecology of glacial forelands has played a pivotal role in advancing theories of primary succession. The naturally occurring short timescale of landscape changes between glacial retreat and ecosystem development found in glacial forelands allows for interpretations of succession over periods of time greater than the life span of researchers (Matthews, 1992;
Walker et al., 2010). Researchers are able to distinguish successional stages by observing patterns throughout the timescale based on the fact that with increasing distance from the glacier, more time has elapsed for the ecosystem to develop. The most foundational study of vegetational chronosequences was conducted in Glacier Bay, Alaska beginning in the early 1920s (Cooper, 1923, 1939) and has been revisited by other scholars since (Crocker and Major, 1955; Reiners et al., 1971; Boggs et al., 2010). Glacier Bay is an ideal location for studying temporal dynamics of primary succession due to its rapidly melting glaciers. As many as 100 kilometers have been exposed in 250 years, revealing terrain that can be relatively accurately dated (Reiners et al., 1971). With repeated studies in this area, a well-defined successional outline has been created with eight successional stages (Reiners et al., 1971). Historical studies of succession within glacial forelands have emphasized the chronosequence, which provided a basis for critical understanding of successional stages.

Modern studies emphasize the need for considering environmental variables to build from the chronosequence at a particular site. The eight successional stages found in Glacier Bay may not be the same stages found in glacier forelands in other geographic locations arising from different environmental histories that lead to different patterns and mechanisms of vegetation succession (Matthews, 1992). Fastie (1995) supports this by arguing a pattern between vegetation and site age could arise from multiple successional pathways. Alternative successional pathways at various sites around the world can be obtained by considering the interrelationships between vegetation, terrain age, and environmental variables (Matthews et al., 1987). This allows researchers to compare findings and generalize successional patterns around the world based on
relationships between vegetation patterns and environmental variables, rather than terrain age which is largely dependent on local history.

Development of primary succession within glacier forelands is largely impacted by the local environmental histories resulting from glacial movement. The terrain exposed during glacial erosion and deposition depends on a variety of factors from the glacier itself and the topography underneath the glacier. Glacier activity such as abrasion, plucking, scouring, cracking, sub-glacial melting, and depositing sediments creates an extremely heterogeneous terrain (Walker and del Moral, 2003). The heterogeneous terrain can create patches of suitable and unsuitable areas for vegetation establishment and growth. Older lateral moraines are important topographic features remaining after glacial retreat that could enhance vegetation development in the foreland by providing a possible supply of seed rain. Other areas of topography remaining from previous glacial erosion, such as bedrock outcrops, can slow the process of vegetation succession (Matthews, 1992). The geocological framework requires researchers to acknowledge and understand the local environmental histories influencing patterns of vegetation development within specific study areas. The Easton foreland has a compelling history that, until recently, has received little attention in the field of successional research.

2.3 Characteristics of the Easton Foreland
The Easton glacier flows down the southwest side of Mount Baker in a steep valley between mid-Holocene age lateral moraines (Figure 2.1). The Easton valley ranges in elevation from 1200 meters to 1640 meters. The southerly aspect makes daytime temperature high, which lowers soil moisture. The climatic trends of the Pacific Northwest and glacial history have
shaped the present terrain and vegetation patterns in the Easton foreland. In this section, I will discuss the climate, geologic history, glacial history, and anthropogenic uses of the Easton foreland.

![Easton Glacier and moraines]

**Figure 2.1**: Easton foreland constrained by mid-Holocene Railroad Grade and Metcalfe lateral moraines (Image from Google Earth Pro, imagery date 7/14/2013)

### 2.3.1 Climate of Easton Foreland

The Pacific Northwest region is characterized by a temperate maritime climate. In 2013, average temperatures in the Easton valley were 17°C in the summer and 4°C in the winter (data from ClimateWNA, 2010). Summer months are typically dry, with the majority of precipitation
falling during the winter as snow. Figure 2.2, a climograph of 2013 data for the Easton valley, reflects the pattern of dry summers and moist winters.

![2013 Climograph Easton Valley](image)

**Figure 2.2: Climograph for Easton Valley, Monthly Averages of 2013.**
*(Climograph has been generated with the Climate WNA v4.62 software package, available at [http://tinyurl.com/ClimateWNA](http://tinyurl.com/ClimateWNA))*

At high elevations of the Cascade mountains, temperatures often drop below freezing between October to April resulting in precipitation falling as snow rather than rain (Bach, 2003).

About eighty percent of precipitation falls during the accumulation season (Pelto, 2015) when storms from the Pacific Ocean deposit moisture on the North Cascades, the first high-elevation orographic feature encountered when these storms make landfall. Typically, during the accumulation season, Mount Baker glaciers gain mass by snowfall above 800 meters (Pelto, 2015). Mount Baker Ski Area, located between 1100-1300 meters, measures and reports winter snowfall totals which are comparable to the snowpack of the Easton valley. This ski area holds a
world record of annual snowfall of 28.55 meters in 1998-1999 and averages 13.5 meters of snowfall per winter (Pelto, 2015). This record-breaking snowfall contributed to the positive mass balance of the Easton glacier during 1998-1999 (Figure 2.3). Over the last decade, Mount Baker Ski Area has experienced general decline in the snowpack (Figure 2.3). Regionally, the Pacific Northwest experienced warming from 1970-2012 of approximately 0.2 degrees Celsius per decade (Abatzoglou et al. 2014) with a related decline in snowpack of fifteen to thirty-five percent between the 1940s and 2003 (Mote et al. 2008). During the spring and summer, the Cascades remain relatively dry, which is the ablation season when glacier mass is lost.

![Mount Baker Ski Area Annual Snowfall](image)

**Figure 2.3: Snowfall totals for Mount Baker Ski Area**

North Cascade temperatures have continued to increase in the twentieth century, with 2015 being the warmest summer in Washington State since 1958 (NOAA, 2015). The record high temperatures during the summer of 2015 were preceded by reduced precipitation amounts in the 2014-2015 winter (Figure 2.6). On May 15, 2015 the Governor of Washington declared a
statewide drought emergency due to historic lows of snowpack and river flow (“Washington Governor”). This decision was made as Washington experienced its ninth driest summer, only receiving fifty-two percent of seasonal average rainfall (NOAA, 2015). These record breaking high temperatures and low precipitation amounts affected Mount Baker’s glaciers significantly. 2015 proved to be “a disastrous year” for North Cascade glaciers which lost five to seven percent of their total glacier volume in one year (Pelto, 2015). Specifically, the Easton glacier suffered historic ablation during the summer of 2015 with a measured retreat of 40 meters (Pelto, 2015; D. Clark, personal communication, September 2015). In addition to temperature and precipitation, wind patterns of the region influence the Easton foreland.

Vegetation development is significantly impacted by complex wind patterns within the Easton foreland. On a large-scale, prevailing Westerly winds are pushed around the Olympic Mountain Range, through the Puget Lowlands, and arrive at Mount Baker with a strong southerly element (Mass, 2008). In the winter months, the polar jet stream brings cold fronts through the area. These winds blow through the mature forests on the Little Ice Age Railroad Grade Moraine before entering the Easton foreland. This prevailing wind brings fine-grain material and seeds to the foreland below. Within the valley, there are local up-valley, southerly winds that can also transport fine-grain material and seeds from the older forest in the lower valley to the younger surfaces in the upper valley (Whelan, 2013). In opposition, northerly
katabatic winds flow off the Easton glacier stripping away fine-grain material and possibly contributing to the inhospitable environment for saplings and seedlings in the upper foreland.

2.3.2 Easton Valley Geology, Soils, and Vegetation

The geologic components within the Easton valley are largely influenced by Mount Baker’s geologic composition and its volcanic eruptive history. Mount Baker is largely composed of Pleistocene and more recent andesites, with the majority being pyroxene andesites (Bockheim and Ballard, 1975). These andesites are the main source of parent material for the glacial foreland. Other materials include plagioclase, hypersthene, and augite (Coombs, 1939). A study of the area (Osborn et al., 2012) identified recent ash deposits and lahars on the south flank of Mount Baker. During the Holocene, four ashes and at least seven lahars were deposited on the flanks of Mount Baker (Kovanen et al., 2001). Over time, these ash layers become buried and influence late-successional development when deep rooting vegetation gain access to these ash deposits (Frenot et al., 1998). Ash eruptions lead to unique soil properties of the surrounding area. Although, ash deposits may have little influence on surfaces less than one hundred years old. Whelan (2013) found the youngest surfaces in the Easton valley were soil types of entisols that develop into inceptisols and spodosols over time when vegetation becomes more continuous. An event that is worth mentioning is a sulfur rich eruption that occurred in the early 1970s (Scott et al., 2005). Today, the sulfur is distributed unevenly throughout the valley. It was hypothesized that the sulfur flow has influenced the high acidity found on young terrain (Whelan, 2013). Additionally, vegetation development appears to avoid the visible zones of sulfur, although sulfur accumulation below ground may also be influencing vegetation patterns.
General vegetation patterns can be described as groundcover with discontinuous *Tsuga mertensiana*. *Pseudotsuga menziesii* and *Abies amabilis* are also present throughout the valley, but are not nearly as dominant as *Tsuga mertensiana*. There is a noticeable lack of *Alnus tenuifolia*, which is normally expected in alpine environments.

### 2.3.3 Easton Glacier History

Glaciers are sensitive indicators of climate change. Annual mass balance measurements are the most accurate method for documenting short term glacier response to climate change (Haeberli, 1995). Annual mass balance is the change in volumetric mass of a glacier in a year, found by the difference between net accumulation and net ablation of snow and ice. Glaciers are constantly fluctuating between net accumulation and net ablation. A glacier with negative mass balance is out of equilibrium and will retreat; a glacier with positive mass balance is out of equilibrium and will advance (Pelto, 2015). Historically, the Easton glacier has fluctuated between phases of retreat and advancement.

In 1912, a photograph was taken by E.D. Welsh from the summit of Loomis Mountain, looking towards Mount Baker with the Easton glacier in the center (Figure 2.4). This photo is likely the earliest and highest quality photo currently available of the south side of Mount Baker. It shows a much greater extent of the Easton glacier than seen today, with its toe where the Scott Paul trail cuts across the foreland (D. Tucker, personal communication, 2016). This 1912 photo answers an important question regarding the exact location of the Easton glacier. Whelan (2013) used 3-D GIS to digitize the estimated location of the furthest 1912 terminus from this photograph, which was used as the lower extent of this study. Interpretation of the 1912 terminus reveals that the Easton Glacier retreated 1.95 kilometers by 2012, with a possibility of
3.05 kilometers of retreat (Whelan, 2013). A century later, photographer John Scurlock teamed up with Mount Baker Volcano Research Center (MBVRC) and the North Cascades Institute to reproduce the photograph for its centennial milestone, in 2012 (Figure 2.5). The dramatic changes observed in these photographs gave rise to this study.
Figure 2.4: 1912 Photograph of Mount Baker by E.D. Welsh

Figure 2.5: 2012 Photograph of Mount Baker by John Scurlock
Between 1912 and 2015, the Easton glacier’s extent and mass balance has been estimated. There is little known about the Easton glacier’s behavior between 1912 to 1940, a 1940 air photo indicated a period of significant retreat was underway (Harper, 1993). Following this retreat phase, an advance interval began for many of Mount Baker’s glaciers (Harper, 1993). This advance interval began at different times for each glacier, but it is estimated that the Easton began advancing after 1954 (Harper, 1993; Pelto 2015). During this period, the Easton terminus advanced 500-600 meters by 1979 (Pelto, 2015). This advance interval lasted until 1990 when it began its retreat that has continued through 2015. These fluctuations in glacier terminus are best explained by climatic variations, measured by precipitation and temperature, in the Mount Baker region between 1940 and 1990 (Harper, 1993; Pelto, 2015). Between 1990 and 2014, the Easton glacier had retreated 320-340 meters from a distinguishable 1990 advance moraine and had lost 14 meters of thickness, about 20 percent of total glacier volume (Pelto, 2015). The cumulative annual mass balance for the Easton glacier was -12.07 meters water equivalent from 1990-2010 (Pelto, 2013, Figure 2.6). The Easton glacier retreated 40 meters in 2015 (D. Clark, personal communication, September 2015; Pelto, 2015). With increased temperatures and reduced
precipitation amounts, all indicators suggest the Easton glacier will continue to retreat until climate change slows.

Figure 2.6: Easton Glacier Mass Balance
Cumulative Mass Balance for 1990-2010 = -12.07 m w.e. (data from Pelto, 2013)

2.3.4 Anthropogenic Uses
The Easton foreland is located within the Mount Baker National Recreational Area within the Mount Baker-Snoqualmie National Forest. This area is cherished by recreationalists: hikers, horseback riders, snowmobilers, campers, and mountaineers. It is relatively accessible from the Schreiber’s Meadow trailhead, which is the access point for the Scott Paul, Park Butte, and Railroad Grade trails. In the winter, snowmobiling is permitted once snow accumulation exceeds two feet. The recreational opportunities surrounding the Easton foreland have
undoubtedly impacted the natural environment. Snowmobiling in particular is destructive for alpine vegetation (Greller et al., 1974) and likely affects vegetation development within the Easton foreland. Snowmobiling damages the natural environment from localized pollution, contamination of the soils, soil erosion, steep slopes, and damages to vegetation (Whelan, 2013; Figure 2.7). The tops of trees are often stunted and sheared due to compaction under snow and snowmobile traffic. Snowmobiling and other recreational activities certainly impact the vegetation development in the Easton foreland; however, there was no way to control for snowmobile or recreational impacts for this study.

Figure 2.7: Evidence of snowmobile pollution
Chapter 3. Methods

The methodological strategy used in this research was adapted from Whelan (2013) for the Easton foreland to create a geoeological understanding of the factors influencing vegetation development. Specifically, these methods were used to answer my research questions: How do vegetation cover, richness, and species diversity change through succession? How are changes in vegetation cover, richness, and species diversity related to environmental variables: distance from glacier, elevation, soil moisture, photosynthetic active radiation (PAR), slope, and aspect?

Chapter 3 is divided into three sections. First, I will discuss the process of choosing a sampling strategy and the data collection process. Then, I will discuss individual site evaluation and describe how each variable was measured. Lastly, the statistical methods are discussed that provide the basis of my results presented in Chapter 4.

3.1 Sampling Strategy

This research sought to identify all the plants that exist in the study area and measure the overall vegetation cover, richness, and species diversity while also measuring environmental variables. My sampling area is approximately 1.45 kilometers long and 0.64 kilometers in width (measured using Google Earth Pro). I chose to employ the commonly used quadrat method. A quadrat is a frame that is laid down to delineate the boundary of the plant community to conduct an intensive study within (Wheater et al., 2011). The quadrat method arose in ecology from the need for precise methods to study the structure and modification of plants over time, an extension of descriptive studies of ecology. The charting and counting of plants within a
quadrat makes it possible to discover the smallest changes and to recognize details of the structure of plant communities (Wheater et al., 2011).

Within the study area, my goal was to locate the exact sites used by Whelan (2013) for placement of a 0.5 square meter quadrat in order to create paired datasets of soil and vegetation in the Easton foreland. Because I was locating Whelan’s (2013) sites, it is important to summarize how each site was selected in that study.

### 3.1.1 Site Selection

Sample sites were selected on glacial deposits in order to understand changes since deposition. The sites chosen by Whelan (2013) carefully considers colluvial/fluvial factors, vegetation patterns, and glacial history as a proxy for surface terrain age, and the elevation gradient. Whelan (2013) delineated the study area within the Easton foreland to be in areas uninfluenced by colluvial/fluvial factors, which left sites between the glacial river and the steep slope of each lateral moraine. Bedrock surfaces were also avoided. Additionally, sites were selected with low relief ($\leq$ 5 percent) to control for slope. Prior to data collection, terrain age zones were delineated based on four major successional stages, originally established by Whelan (2013). These zones were based on estimated historic glacial extent from photographs and literature: Zone 0 = 0 years, Zone I = 1-25 years, Zone II = 26-40 years, Zone III = 41-75 years, Zone IV = 76-100 years (Figure 3.1). Vegetation patterns of each zone are identifiable from photographs, but this study refines the zones with specific species. Zone 0 is on glacial ice from which one can infer initial conditions with the glacier present, but consists of no vegetation. Zone I consists of rare pioneer species where establishment and growing conditions are extremely harsh. Within Zone II, vegetation is sparse but becomes more established. Zone III is
a transition zone characteristic of patchy vegetation prior to the continuous forest found in Zone IV.

Figure 3.1: Terrain Age Zones showing distinct patterns of vegetation (Zone 4 photo by Andy Bach)

Surface ages were estimated within the terrain age zones based on glacial history (Harper, 1993; MBVRC photos, 2012), air photo interpretation, and on-the-ground evaluation of characteristic moraines. Whelan (2013) extended the known glacial timeline using the historic photograph of 1912 from MBVRC, establishing the lower extent of one hundred years of terrain age. Only three surface ages were identifiable for Whelan: 0, ≤ 20, ≤ 100 years; however, my research refined the approximate location of the 1940 terminus based on literature (Harper, 1993; Figure 3.2).
Figure 3.2: Study Sites within Terrain Age Zones
This coarse timeline of terrain age is due to the fact that there is no record of the exact location of the Easton glacier terminus between 1912 and 1940; however, distance from glacier can serve as a proxy for terrain age, under the assumption that as distance away from the glacier increases time since exposure also increases (Matthews, 1992). This logic is not without flaws, since the Easton glacier had a period of advancement between 1956 and 1990 (Harper, 1993). For the purposes of this research, distance from glacier and time since deglaciation are considered linear, as the exact location of the advancement is unknown (Matthews, 1992). The interconnectedness of deglaciation age, distance from glacier, and terrain age zones allows for inferences of succession to be based on the distance from the glacier.

**3.1.2 Locating Sites**

Within the terrain age zones, Whelan (2013) used random number generators to select coordinates for sample sites. To relocate Whelan’s (2013) sampling sites, I programmed the latitude and longitude he had collected in 2012 for all of the sites into a Garmin GPSMAP 60CSx unit. The GPS directs the user to the location while walking by giving direction and distance on the screen. Once the GPS registered that we had relocated the site, I tossed a quadrat to the ground for random selection. While the main goal was to relocate Whelan’s (2013) sites, my final site selections varied slightly (Figure 3.3) due to a severe geomagnetic storm that occurred during my fieldwork which introduced error into the GPS signal. The geomagnetic storm occurred from June 21-23, 2015, coinciding with my fieldwork and was the second largest event of the present solar cycle (USGS, 2015). During a geomagnetic storm, a series of large concentrations of solar wind are ejected from sunspots. These large concentrations enter the Earth’s magnetosphere, injecting electrically charged particles that can create magnetic disturbances on Earth. While this was a particularly intense storm in general, magnetic storms...
are often especially intense at higher latitudes. During this particular magnetic storm, the
direction of the Earth’s magnetic field fluctuated by almost 10 degrees in less than an hour at the
USGS Barrow observatory in northern Alaska (Love et al., 2015). This geomagnetic storm
noticeably influenced our GPS signals in the Easton foreland. Although I was unsuccessful in
resampling the exact locations as Whelan (Figure 3.3), it is still possible to compare soil and
vegetation, just at a broader vegetation zone scale throughout the whole valley rather than at
each site.
Figure 3.3: Comparison of study sites showing variance due to geomagnetic solar storm
3.2 Data Collection

This section will describe the methods used to identify and quantify vegetation and environmental variables within each quadrat at fifty-three study sites throughout the Easton foreland. The fieldwork was conducted June 19-21, 2015 and June 27, 2015, with the immense help of a hard-working team of researchers. Each person had a specific variable they measured the entire weekend in order to maintain consistency in the measurements. At each site, a 0.5 square meter quadrat was assembled and laid down to designate the sampling area. Within each quadrat, the following variables were quantified.

*Plant Identification*

Vascular plants and trees that were rooted within the quadrat were identified using Hitchcock and Cronquist (1973) and Pojar and MacKinnon (2004). Under the restraints of my research permit from the Forest Service, I was not allowed to take samples out of the valley. The majority of plants were identifiable in the field; however, for those that were questionable I took high-quality photographs (Figure 3.4) and wrote specific observations to identify upon return to Western Washington University.
Vegetation Cover

Vegetation cover was estimated as the percentage of ground covered by vascular plants within the quadrat. This was done by visual estimation of the percentage of the area each species filled of the quadrat frame to the nearest percent. Visual estimation of percent cover is a commonly used method (Ter-Mikaelian, 1999); however, it is limited by its subjectivity. To reduce subjectivity, the same person quantified percent cover at each quadrat but compared their estimation with the estimation of another researcher in the team while in the field. If there was a difference between estimations, the average value was recorded. Additionally, vertical photographs were taken of each quadrat, showing examples of measured percent cover (Figure 3.5, Figure 3.6).
Figure 3.5: Example of Vegetation Cover - Estimated at 2 Percent

Figure 3.6: Example of Vegetation Cover - Estimated at 25 Percent
**Vegetation Richness**
Vegetation richness was quantified by counting the number of species present in each quadrat (Pielou, 1975).

**Species Diversity**
Species diversity was quantified by using Shannon-Wiener Diversity Index (H'). It assumes the individuals are randomly sampled and that all species are represented in the sample (Pielou, 1975). The Shannon index is weighted by the abundance of each species and is defined by:

\[ H' = - \sum p_i \ln p_i \]

where \( p_i = n_i/N \)

\( n_i = \# \text{ of individuals of species } i \)

\( N = \text{total } \# \text{ of individuals of species } i \)

In general, communities with more species are considered to be more diverse with typical values ranging from 1.5 to 3.5 and rarely exceeding 4 (Magurran, 2004).

**Distance from glacier**
The GPS points of each study site, including the toe of the Easton glacier, were digitized into a feature class using ArcGIS. Then, Euclidian distance was calculated from the point at the toe of the glacier, using Easting and Northing values from the NAD 1983 State Plane Washington North (meters) projected coordinate system.

**Elevation**
Elevation was measured in meters above sea level using a Garmin GPSMAP 60CSx unit.
**Slope**
Slope was measured using an iPhone® inclinometer in degrees. The iPhone® inclinometer application has been shown to be as reliable as a traditional gravity bubble inclinometer (Kolber et al., 2013).

**Aspect**
Aspect is the direction or azimuth that a slope faces and was measured in degrees using an iPhone® Compass application. Raw values of aspect are ill-suited for quantitative analysis of vegetation because 1 degree is adjacent to 360 degrees: their values illustrate a large difference but the aspect is very similar (McCune and Grace, 2002). Thus, aspect was transformed to provide useful information in relation to this study. Following Andreis (et al., 2001) values of aspect were cosine transformed where values of -1 indicate a south-facing slope, and values of +1 indicate a north-facing slope.

**Photosynthetic Active Radiation**
Photosynthetic active radiation (PAR) was measured using a Quantum Sensor, LI-190/R Light Meter that averages 60 values in 15 seconds and reports a single averaged value. Due to the large variations in PAR throughout the day, it is best to measure it at solar noon every day to see the solar variations at a site (Ter-Mikaelian, 1999). In this study, PAR was measured throughout the day due to time limitations and ruggedness of the natural environment. This is a limitation to the usefulness of individual PAR values; however, a pattern of PAR throughout the valley can still be assessed for the days measured.

**Soil Moisture**
Soil moisture was measured as a percentage of volumetric water content at a fixed depth of twelve centimeters using a VG-METER-200 with a VH400 soil sensor meter. Ten
measurements of soil moisture were taken within each quadrat and the results were averaged. To reduce confounding effects of rain events, our fieldwork was conducted during a period of dry weather. The first rain event in a two-week period occurred on June 18, 2015, one day before our field sampling weekend. No rain event occurred during our field sampling weekend and the sampling was completed over a short period of time.

3.3 Statistical Methods

Correlation and regression statistical tests were run in an effort to understand the main purposes of this study: how vegetation cover, richness, and species diversity change through succession, and how changes in vegetation cover, richness, and species diversity are related to environmental variables: distance from glacier, elevation, soil moisture, photosynthetic active radiation (PAR), slope, and aspect. We considered vegetation variables as dependent variables and environmental variables as independent variables. The dependent variables were run against independent variables throughout the entire valley and for each terrain age zone. The statistical significance of all tests was assessed at 95% confidence interval.

All dependent variables were non-normally distributed according to the results of normality tests for the entire dataset, guiding the decision to perform the non-parametric Kruskal-Wallis test. This test determines whether the groups being compared have the same population median (Everitt, 1998). In this research, it tells whether difference between terrain age zones is statistically significant.

Spearman’s Rank-Order Correlation (rho) was used to determine the strength of the relationship between the dependent and the six independent variables, assuming no casual relationships between the variables. Due to the linear requirement of variables for this test, the
dependent variables were log transformed +1 (McCune and Grace, 2002; McGrew and Monroe, 2000). Partial correlations were also performed to address multicollinearity among variables. Interpretation of the correlation results are guided by the ‘Rule of Thumb’ published by Malawi Medical Journal (Mukaka, 2012), where a Correlation Coefficient of 0.90 to 1.00 = Very High, 0.70 to 0.90 = High, 0.50 to 0.70 = Moderate, 0.30 to 0.50 = Low, 0.00 to 0.30 = Negligible. Partial Spearman’s Correlations were performed to address multicollinearity among environmental variables.

Regression analysis was conducted to estimate the influence of independent variables on the dependent variable, which requires the assumption that certain environmental variables do influence and/or affect vegetation variables through a functional relationship (McGrew and Monroe, 2000). To deal with the non-normality the dataset was log transformed. Findings from the correlation tests were used to guide the selection of independent variables for regression analysis by narrowing in on the environmental variables that have the highest correlation to the vegetation variables. As a result, a logarithmic function was developed for vegetation cover versus distance from glacier due to the nature of the data, and a linear function was developed for vegetation richness versus distance from glacier.
Chapter 4. Results and Discussion

4.1 Results of Species Distribution

This section outlines the specific species found in the Easton foreland and categorizes the species based on terrain age zones as a temporal analysis of primary succession.

4.1.1 Large-scale Species Distribution

Fifteen vascular plant species were identified throughout the Easton valley (Table 4.2), nomenclature follows Hitchcock & Cronquist (1973). This section outlines the plant species found in the foreland on a large-scale in an effort to survey the vegetation that currently exists in the Easton foreland.

The species within the foreland have been categorized within each terrain age zone, illustrating a chronosequence of succession. The zones are as follows: Zone 0) a barren zone, 0 years old, most recently exposed and closest to the glacier; Zone I) a 0 to 26 year old zone characterized by rare vegetation and existence of early pioneer species Luetkea pectinata, Poa alpina, Juncus drummondii, Lupinus polyphyllus, Saxifraga tolmiei. Interestingly, Zone I also has occasional seedlings of Tsuga mertensiana. Tsuga mertensiana is considered a climax species; however, it has been found to be a pioneer on glacial moraines in British Columbia and Alaska (“Index of Species Information”). Tsuga mertensiana seeds are primarily dispersed by wind, due to its winged pollen (Means, 1990). At the Easton valley, mature, seed producing Tsuga mertensiana occur topographically atop of the Railroad Grade moraine and are poised to be relocated downwind, thus likely acting as a seed source for the valley. Zone II) 27 to 40 year old zone dominated by sparse areas of Saxifraga tolmiei, Juncus drummondii, Luetkea pectinata, and Phyllocladus empetriiformis, with occasional Tsuga mertensiana; Zone III) 41 to 75 year old zone containing patches of Luetkea pectinata in its highest abundance, Lupinus polyphyllus, Juncus drummondii, Luzula
spicata, Arctostaphylos uva-ursi and scattered Tsuga mertensiana; Zone IV) 76 to 100 year old zone, characterized by the transition from low herbaceous plants to a more developed, continuous forest. Tsuga mertensiana and Abies amabilis are often found alongside each other (“Index of Species Information”). This zone contains the highest vegetation cover, richness, and diversity among plant species (Table 4.1): Lupinus polyphyllus, Luetkea pectinata, Chamerion angustifolium, Poa alpina, Carex macloviana, Arnica latifolia, Salix sitchensis, Fragaria vesca, Luzula spicata, and Arctostaphylos uva-ursi. The boundaries between each zone are apparent from visual inspection (Figure 3.1), with the most evident being the boundary between Zones II and III. The demarcation between Zone III and IV is less clear; however, it was noted by Paul Whelan while in the field in 2015 that Zone IV had encroached northward from when he conducted his research in 2013. The distribution of plant species within this foreland indicate pioneer species colonize the terrain between 20-40 years after glacial retreat and late successional species are established within 60-75 years following glacial retreat. This distribution agrees with the timing of plant establishment within other glacial forelands around the world (Frenot et al., 1998; Andreis et al., 2001) and justifies using the designated terrain age zones as a gradient for primary succession within the Easton foreland.
Table 4.1 Characteristics of Terrain Age Zones

<table>
<thead>
<tr>
<th>Terrain Age Zones</th>
<th>0</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years Since Deglaciation</td>
<td>0</td>
<td>0-26</td>
<td>26-40</td>
<td>40-75</td>
<td>75-100</td>
</tr>
<tr>
<td>Mean Elevation (m)</td>
<td>1625.25</td>
<td>1589.73</td>
<td>1532.22</td>
<td>1474.75</td>
<td>1363.82</td>
</tr>
<tr>
<td>Elevation Range (m)*</td>
<td>25</td>
<td>155</td>
<td>80</td>
<td>60</td>
<td>165</td>
</tr>
<tr>
<td>Transformed Aspect **</td>
<td>-0.71 +/-0.35 (South)</td>
<td>-0.70 +/-0.27 (South)</td>
<td>-0.32 +/-0.70 (South)</td>
<td>-0.34 +/-0.78 (South)</td>
<td>-0.56 +/-0.61 (South)</td>
</tr>
<tr>
<td>Mean Slope (%)</td>
<td>-16.75 +/-10.44</td>
<td>-11.27 +/-7.81</td>
<td>-9.22 +/-4.27</td>
<td>-10.375 +/-5.26</td>
<td>-17.59 +/-8.65</td>
</tr>
<tr>
<td>Vegetation Cover (%)</td>
<td>0</td>
<td>9.8 +/-21.45</td>
<td>24.45 +/-5.79</td>
<td>60.69 +/-30.62</td>
<td>78.82 +/-5.03</td>
</tr>
<tr>
<td>Species Richness</td>
<td>0</td>
<td>0.733 +/-1.16</td>
<td>1.78 +/-1.20</td>
<td>2.38 +/-0.74</td>
<td>2.71 +/-1.36</td>
</tr>
<tr>
<td>Shannon Diversity H'</td>
<td>0</td>
<td>1.06</td>
<td>1.35</td>
<td>0.88</td>
<td>1.73</td>
</tr>
<tr>
<td>Most Abundant Species</td>
<td>N/A</td>
<td><em>Luetkea pectinata, Poa alpina</em></td>
<td><em>Saxifraga tolmiei</em></td>
<td><em>Luetkea pectinata</em></td>
<td><em>Lupinus polyphyllus</em></td>
</tr>
</tbody>
</table>

Numbers were measured in the field. Values are Mean +/- Standard Deviation

*Elevation range is difference between highest and lowest elevation

**Cosine transformed Aspect, where -1 indicates South facing slope and +1 indicates North facing slope
Table 4.2 Relative Abundance of Species within Terrain Age Zones

<table>
<thead>
<tr>
<th>Species</th>
<th>Total Relative Abundance (%)</th>
<th>Zone I</th>
<th>Zone II</th>
<th>Zone III</th>
<th>Zone IV</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Tsuga mertensiana</em> (Mountain Hemlock)</td>
<td>9.81</td>
<td>0.62</td>
<td>2.12</td>
<td>1.07</td>
<td>17.79</td>
</tr>
<tr>
<td><em>Abies amabilis</em> (Pacific Silver Fir)</td>
<td>0.41</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.80</td>
</tr>
<tr>
<td><em>Lupinus polyphyllus</em> (Large-Leaved Lupine)</td>
<td>19.73</td>
<td>10.49</td>
<td>0.00</td>
<td>9.12</td>
<td>30.25</td>
</tr>
<tr>
<td><em>Luetkea pectinata</em> (Partridge Foot)</td>
<td>44.15</td>
<td>44.44</td>
<td>30.69</td>
<td>75.60</td>
<td>20.51</td>
</tr>
<tr>
<td><em>Phyllodoce empetriformis</em> (Pink-mountain heath)</td>
<td>0.33</td>
<td>0.00</td>
<td>2.12</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td><em>Chamerion angustifolium</em> (Fireweed)</td>
<td>0.65</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.28</td>
</tr>
<tr>
<td><em>Juncus drummondii</em> (Drummond's Rush)</td>
<td>5.97</td>
<td>12.35</td>
<td>20.63</td>
<td>3.75</td>
<td>0.00</td>
</tr>
<tr>
<td><em>Poa alpina</em> (Alpine Bluegrass)</td>
<td>5.31</td>
<td>21.60</td>
<td>2.65</td>
<td>0.00</td>
<td>4.01</td>
</tr>
<tr>
<td><em>Saxifraga tolmiei</em> (Tolmie's Saxifrage)</td>
<td>5.15</td>
<td>1.23</td>
<td>32.28</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td><em>Carex macloviana</em> (Falkland Island Sedge)</td>
<td>1.88</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>3.69</td>
</tr>
<tr>
<td><em>Arnica latifolia</em> (Mountain Arnica)</td>
<td>1.31</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>2.56</td>
</tr>
<tr>
<td><em>Salix sitchensis</em> (Sitka Willow)</td>
<td>0.25</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.48</td>
</tr>
<tr>
<td><em>Fragaria vesca</em> (Woodland Strawberry)</td>
<td>2.70</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>5.29</td>
</tr>
<tr>
<td><em>Luzula spicata</em> (Spiked wood-rush)</td>
<td>3.03</td>
<td>0.00</td>
<td>0.00</td>
<td>3.75</td>
<td>3.69</td>
</tr>
<tr>
<td><em>Arctostaphylos uva-ursi</em> (Kinnikinnick)</td>
<td>0.25</td>
<td>0.00</td>
<td>0.00</td>
<td>0.27</td>
<td>0.32</td>
</tr>
</tbody>
</table>
4.2 Results of Statistical Tests: Vegetation Cover

This section describes the results of vegetation cover throughout the Easton foreland to answer the main research question: How do vegetation cover, richness, and species diversity change through succession?

4.2.1 Kruskal-Wallis

Due to the non-normal distribution of the dataset the Kruskal-Wallis test was performed to test the statistical significance of vegetation cover between terrain age zones. Using a 0.05 level of significance, the Chi-Squared statistic of 41.49 is greater than the critical value at 3 degrees of freedom (McGrew and Monroe, 2000). Therefore, there is evidence of significant difference in vegetation cover between each terrain age zone. Vegetation cover does significantly increase between each vegetation zone, validating the used vegetation zones as a sampling unit.

<table>
<thead>
<tr>
<th>Test Statistic</th>
<th>Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chi-Squared, $X^2$</td>
<td>41.49</td>
</tr>
<tr>
<td>P-Value</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Table 4.3 Kruskal-Wallis: Vegetation Cover

4.2.2 Spearman’s Rank-Order Correlation

In order to determine the strength and relationship of vegetation cover in relation to the six independent variables, Spearman’s Rank-Order Correlation was employed. It is important to consider that all these independent variables, and many others not considered in this study, interact with each other to influence development of vegetation throughout primary succession, as shown in the correlogram (Figure 4.1). Additionally, it is crucial to remember that correlations indicate associations, not causality. As shown in Table 4.4, vegetation cover is highly correlated with distance ($r = 0.86, p$-value =<0.001) and elevation ($r = -0.82, p$-value =<0.001) and
moderately correlated with PAR ($r = -0.59$, $p$-value $< 0.001$). Vegetation cover is not statistically significantly related to aspect, slope, or soil moisture at these sites.

**Figure 4.1: Corrolegram for Vegetation Cover and Environmental Variables**

**Table 4.4 Spearman’s Correlation: Vegetation Cover**

<table>
<thead>
<tr>
<th></th>
<th>Distance</th>
<th>Elevation</th>
<th>Aspect</th>
<th>Slope</th>
<th>Photosynthetic Active Radiation</th>
<th>Soil Moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>0.86</td>
<td>-0.82</td>
<td>0.05</td>
<td>-0.17</td>
<td><strong>-0.59</strong></td>
<td>-0.21</td>
</tr>
<tr>
<td>$p$-value</td>
<td><strong>&lt;0.001</strong></td>
<td><strong>&lt;0.001</strong></td>
<td>0.95</td>
<td>0.25</td>
<td><strong>&lt;0.001</strong></td>
<td>0.10</td>
</tr>
</tbody>
</table>
4.2.3 Partial Correlations

Distance, elevation, and PAR were the three most highly correlated environmental variables to vegetation cover (Table 4.4). However, the multicollinearity among these environmental variables raises concerns for the strength of the correlations. To address the multicollinearity, partial correlations were run to examine the relationship between two variables, while controlling the third. Since elevation and distance are highly correlated to each other ($r = -0.93; p\text{-value} = <0.001$), distance and PAR are moderately correlated with to each other ($r = -0.66; p\text{-value} = <0.001$), and elevation and PAR are moderately correlated to each other ($r = 0.60, p\text{-value} = <0.001$), performing partial correlation between vegetation cover and each environmental variable while holding distance, elevation, and PAR constant shows a more representative relationship (McGrew and Monroe, 2000).

The results of the partial correlations indicate that vegetation cover is highly correlated with distance and elevation when PAR is held constant. Additionally, partial correlations tease out the relationship between elevation and distance: vegetation cover and distance are more highly correlated than vegetation cover and elevation (Table 4.5).

<table>
<thead>
<tr>
<th>Cover + Distance (PAR Constant)</th>
<th>Cover + Distance (Elevation Constant)</th>
<th>Cover + Elevation (Distance Constant)</th>
<th>Cover + PAR (Elevation Constant)</th>
<th>Cover + PAR (Distance Constant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r = 0.77$</td>
<td>$r = 0.46$</td>
<td>$r = 0.10$</td>
<td>$r = -0.71$</td>
<td>$r = -0.22$</td>
</tr>
<tr>
<td>$p\text{-value} = &lt;0.001$</td>
<td>$p\text{-value} = &lt;0.001$</td>
<td>$p\text{-value} = 0.48$</td>
<td>$p\text{-value} = &lt;0.001$</td>
<td>$p\text{-value} = 0.12$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$r = -0.06$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$p\text{-value} = 0.647$</td>
</tr>
</tbody>
</table>
4.2.4 Logarithmic Regression

The relationship between vegetation cover and distance from the glacier is examined further through logarithmic regression. A logarithmic function can be used to estimate the influence of the independent variable on the dependent variable by examining the relative predictive power of independent variables on a dependent variable (Urdan, 2001). The complete regression equation is:

\[
Vegetation\ Cover = 0.79 + (0.002) \ln \text{Distance}(\text{meters})
\]

This equation can be used to find the percent vegetation cover at a given distance from the glacier. It is important to note that this equation is bounded by the distance values found in this study, and it would be invalid to apply this equation to estimate vegetation cover outside of the bounds of 0 to 1946 meters away from the Easton glacier.
4.3 Results of Statistical Tests: Vegetation Richness

This section describes the results of vegetation cover throughout the Easton foreland to answer the main research question: How do vegetation cover, richness, and species diversity change through succession?

4.3.1 Kruskal-Wallis

The Kruskal-Wallis test was also performed to compare terrain age zones for differences in vegetation richness. Using a 0.05 level of significance, the Chi-Squared statistic of 28.24 is greater than the critical value at 3 degrees of freedom (McGrew and Monroe, 2000). There is evidence of significant difference in vegetation richness between the terrain age zones (Table 4.6), suggesting that successional stage does change over time as hypothesized.
**Table 4.6 Kruskal-Wallis: Vegetation Richness**

<table>
<thead>
<tr>
<th>Test Statistic</th>
<th>Richness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chi-Squared, $X^2$</td>
<td>28.24</td>
</tr>
<tr>
<td>P-Value</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

### 4.3.2 Spearman’s Rank-Order Correlation

Spearman's Rank-Order Correlation was performed to determine the strength and relationship of vegetation richness in relation to the six independent variables. As shown in Table 4.7, vegetation richness indicates a high correlation with distance ($r = 0.74$, $p$-value = <0.001), a moderate correlation with elevation ($r = -0.629$, $p$-value = <0.001), and a low correlation is present with photosynthetic active radiation ($r = -0.459$, $p$-value = <0.001).

Vegetation richness is not statistically significantly related to slope, aspect, or soil moisture at these sites.
These tests verify the hypothesis that vegetation richness is most correlated by distance and elevation throughout succession; as distance from the glacier increases, vegetation richness increases and as elevation decreases, vegetation richness increases. The negative relationship with PAR indicates as vegetation richness increases, PAR decreases.
4.3.3 Partial Correlations

Distance, elevation, and PAR were the three significantly correlated environmental variables to vegetation richness. Similar to the results from vegetation cover, the multicollinearity among these environmental variables raises concerns for the strength of the correlations. To address the multicollinearity, partial correlations were run to examine the relationship between two variables, while controlling the third. Since elevation and distance are highly correlated to each other \((r = -0.93; p\text{-value} = <0.001)\), distance and PAR are moderately correlated to each other \((r = -0.66; p\text{-value} = <0.001)\), and elevation and PAR are moderately correlated to each other \((r = 0.6, p\text{-value} = <0.001)\), performing partial correlation between vegetation richness and distance while holding elevation and PAR constant shows a more representative relationship (McGrew and Monroe, 2000).

The results of the partial correlations indicate that vegetation richness is moderately correlated with distance when elevation and PAR is held constant. Richness is also moderately correlated with elevation when PAR is held constant, but there is a negligible relationship when distance is constant. Richness is moderately correlated with PAR when elevation is held constant and there is a negligible relationship when distance is held constant. Additionally, partial correlations sifted out the relationship between elevation and distance: vegetation richness and distance are more highly correlated than vegetation richness and elevation (Table 4.8).
4.3.4 Bivariate Regression

Bivariate regression is a logical extension of correlation that further describes the nature of the relationship between variables (McGrew and Monroe, 2000). Bivariate regression was used to examine the relationship between vegetation richness and distance from glacier due to a more linear relationship than what was observed between vegetation cover and distance. Bivariate regression examines the influence of the independent variable on the dependent variable by examining the relative predictive power of independent variables on a dependent variable (Urdan, 2001). Due to the multicollinearity found between distance, elevation, and PAR, bivariate regression was performed using only distance. Distance was used in the regression model as the independent variable influencing the dependent variable, vegetation richness. The complete regression equation is:

\[
Vegetation \text{ Richness (No. of Species)} = 0.48 + 0.002 \times \text{Distance (meters)}
\]

This equation indicates that for every unit increase of distance away from the glacier (1 meter), vegetation richness is increased by 0.002 species. This low increase in species is appropriate given the low number of total species found within the Easton foreland (Figure 4.4). An essential pattern is evident from looking at the data in Figure 4.4 that justifies distance from

<table>
<thead>
<tr>
<th>Table 4.8 Partial Correlations: Vegetation Richness</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Richness + Distance (PAR Constant)</strong></td>
</tr>
</tbody>
</table>
| \( r = 0.66 \)  
\( p\text{-value} = <0.001 \) | \( r = 0.55 \)  
\( p\text{-value} = <0.001 \) | \( r = 0.25 \)  
\( p\text{-value} = 0.077 \) | \( r = -0.50 \)  
\( p\text{-value} = <0.001 \) | \( r = -0.13 \)  
\( p\text{-value} = <0.001 \) | \( r = 0.06 \)  
\( p\text{-value} = 0.649 \) |
glacier correlating most strongly with vegetation richness: the extreme values of 0 are at the sites closest to the glacier (blue), while the values of 5 species are found furthest from the glacier (green). In the middle of the foreland, richness values maintained evenness of 1-3 species.

![Richness vs. Distance](image)

**Figure 4.4: Map highlighting extreme values for vegetation richness and distance from glacier**

### 4.4 Summary of Statistical Results

The non-linear relationship between vegetation cover and distance from glacier indicates rapid growth and establishment of vegetation initially, patchy development once conditions become favorable after more time has elapsed since glacier retreat, and eventual plateauing of vegetation cover furthest away from the glacier. This plateau could be the maximum vegetation
cover sustained in this valley. The linear trend between vegetation richness and distance was expected due to the dense forest developing farthest from the glacier toe. Slope, aspect, PAR, and soil moisture were not useful variables in explaining vegetation development in this study. This is likely due to the limitations of the measurements of these variables and the evenness of these variables throughout the study area. Cluster analysis was performed to examine homogeneity of these variables throughout the valley. Moran’s I (Global Statistic) was run to assess spatial autocorrelation that identifies patterns of clustering based on location and feature values (Table 4.9). Soil moisture and aspect exhibit a random spatial pattern. PAR and slope exhibit a statistically significant clustered pattern.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Moran’s I</th>
<th>Z-Score</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Moisture</td>
<td>-0.0075</td>
<td>0.1594</td>
<td>0.8733</td>
</tr>
<tr>
<td>Aspect</td>
<td>-0.0853</td>
<td>-0.708345</td>
<td>0.4787</td>
</tr>
<tr>
<td>PAR</td>
<td>0.4390</td>
<td>4.8273</td>
<td>0.0001</td>
</tr>
<tr>
<td>Slope</td>
<td>0.1988</td>
<td>2.3131</td>
<td>0.0207</td>
</tr>
</tbody>
</table>

Since the global statistic determines clustering based on locations, a local statistic test was also run to focus only on the values of each variable throughout the valley. Anselin’s Local Moran’s I identifies clusters of a feature with values similar in magnitude and identifies spatial outliers. This test shows that the majority of the sites for soil moisture, PAR, aspect, and slope are not significantly clustered, explaining the non-significance as a factor of vegetation development (See Appendix B). These results indicate that on a small-scale of one hundred years since deglaciation and in an area of approximately 1.45 kilometers long by 0.64 kilometers
in width, environmental variables of soil moisture, PAR, slope, and aspect do not provide significant contributions to explaining patterns of vegetation development because the values do not exhibit much variability. A chronosequence may be sufficient to explain vegetation development at this scale.

4.5 Discussion of Statistical Results

4.5.1 Vegetation Cover

Patterns of vegetation cover suggest a period of slow rates of establishment initially, with vegetation cover remaining patchy until a strong trend emerges of increasing vegetation cover in late stages of primary succession and farthest away from the glacier. Vegetation cover was highly heterogeneous from Zones I-III, indicating patchiness prior to the development of the continuous forest. A statistically significant difference in vegetation cover between zones demonstrates that the vegetation, at least in the early stages, develops incrementally. Correlation analysis showed a strong trend of increasing vegetation cover with the environmental variables of distance, elevation, and PAR. Partial correlations suggest distance to be the most correlated variable when elevation and PAR were held constant. Results from the logarithmic regression model defines the best estimate of the relationship between vegetation cover and distance, showing a non-linear relationship. This slow but steady increase in vegetation cover seen in the Easton foreland is in agreement with other studied forelands (Burga, 2010). Additionally, the non-linear relationship is supported by the possibility of multiple starting points of vegetation cover within the valley, due to wind bringing seeds from the Little Ice Age moraines. This also suggests there is a maximum amount of vegetation cover that can be sustained in the valley and is reached within 75-100 years following the disturbance.
In almost all glacier foreland studies, vegetation cover increases over time. Yet specific patterns in vegetation cover vary widely among locations. A general successional trend that can explain vegetation cover is a sigmoidal tendency which has been found in the Alps is an initial slow period from 0-20 years then a steady increase between 20-100 years, and a plateau at one-hundred percent cover after 100 years (Zollitsch, 1969 as cited in Matthews, 1992). In northern Sweden, Stork (1963) also documents sigmoidal trend with a slow initial phase in vegetation cover from 10-15 years, a rapid increase from 15-50 years, and a plateau of one hundred percent cover at 100 years. The sigmoidal trend reflects the pattern in the Easton foreland with cover averages below 50 percent until Zone III, approximately 75 years after glacial retreat.

Vegetation cover largely depends on the interaction between environmental factors and biological controls, such as patterns of immigration, species interaction, and soil nutrient availability; thus, varied trends have been documented. Contrary to the Easton foreland, linear trends have been found where vegetation cover and number of species increase steadily with time (Conen et al., 2007). Severe, hostile environments for vegetation development are likely to see minimal values of percent cover (Frenot et al., 1998; Arnalds et al., 1987) whereas hospitable environments may reach 90 percent cover within a short period of time (Decker, 1966 as cited in Matthews, 1992).

Local comparison with the Coleman foreland on Mount Baker corroborates the values and pattern of vegetation cover found in the Easton foreland. Vegetation cover increased from 25% to 100% over approximately a 180-year timeline (Jones et al., 2005), with generally higher values in each zone than what was found in the Easton foreland. These higher values are likely due to the differences in elevation between the Coleman and Easton forelands. The highest
average elevation of the Coleman foreland is 1258 meters while the Easton is 1590 meters. The lower elevation along with the northerly aspect in the Coleman foreland results in cooler temperatures and slower vegetation establishment and growth.

A previous study of the Easton foreland found slightly lower values of vegetation cover with an overall average of 31.44 percent (Whelan, 2013). A weaker negative relationship between vegetation cover and elevation was also found by Whelan (2013) with a Spearman’s $r = -0.446$, compared to -0.82 found in this study. This difference is likely due to lower number of sampled quadrats in each terrain age zone within this study than Whelan’s.

Patterns of vegetation cover can be explained more specifically by the environmental variables. Distance, elevation, and PAR are the three variables that significantly explain patterns of vegetation cover in the Easton foreland. The strong positive relationship between vegetation cover and distance can be explained by the space-for-time substitution, where with greater distance from the glacier, more time has elapsed, allowing for soil development and establishment of vegetation (Matthews, 1992). The non-linear relationship between cover and distance may suggest the advancement of the Easton glacier had a significant impact on vegetation development, which should be investigated further. Vegetation cover increasing with distance from the glacier indicates different species colonizing progressively older terrain, the trend that originally inspired ecologists to study recently deglaciated terrain (Coaz, 1887 as cited in Matthews, 1992). While distance from the glacier is the most correlated variable with vegetation cover, the trends in cover are also correlated with elevation and PAR.

The negative relationship between vegetation cover and elevation is spurious as shown by the partial correlations tests, which proved distance to be more strongly correlated with
vegetation cover than elevation. The negative relationship with vegetation cover and PAR might be explained by the increase in vegetation canopy that could block or scatter incoming PAR (McCree, 1981). This creates an inverse causality in the relationship where vegetation influences PAR. This is an important relationship, as PAR can be used as a surrogate for visually measuring vegetation cover (Ter-Mikaelian, 1999). All of the other environmental variables measured in this study influenced vegetation. The findings of this study are in agreement with the correlation found at the Ontario Forest Research Institute arboretum, where cover and PAR were highly negatively correlated \((r = -0.8546)\) (Ter-Mikaelian, 1999). These microsite conditions create the base for the larger scale patterns of vegetation cover increasing over time and space as the glacier retreats, leaving behind terrain available for development of soil and colonization of vegetation.

4.5.2 Vegetation Richness

Results from statistical tests indicate vegetation richness increases slowly throughout succession in the Easton foreland and maintains low values at all sites. Correlation analysis showed a high trend of increasing vegetation richness with distance, a moderate relationship with elevation, and poor relationship with PAR. Partial correlation suggests moderate correlation with distance when PAR and elevation are held constant, and a moderate correlation with PAR when elevation is held constant, but a negligible correlation with elevation when distance is held constant. The bivariate regression model provides evidence of low values of number of species increasing with distance from the glacier.

Temporal changes in species richness tend to increase in the early stages of succession and decrease slightly from a subclimactic maximum (Pielou, 1975). Specific rates and values vary significantly depending on location but generally species richness decreases with increasing
elevation, in proportion to the available land area (Körner, 2000). Patterns of species richness tend to be relatively slow in severe environments as seen in sub-Antarctica (Smith, 1984), while low- to sub-alpine areas experience rapid increases in richness (Sommerville et al., 1982). The Easton foreland shows relatively slow rates of vegetation richness and low numbers of vegetation richness, peaking at 5 species in one quadrat the 100-year terrain zone. A probable explanation for the low richness in the Easton foreland can be attributed to limitations of dispersal mechanisms for species to arrive in the foreland. The steep moraine ridges surrounding the foreland provide a seedbank for the foreland, but species must have characteristics of wind dispersal to immigrate to the foreland. *Leutkea pectinate* and *Epilobium angustifolium* are documented on Railroad Grade moraine, both exhibiting wind-blown seeds (Washington Native Plant Society, 2015). This low richness is also supported by the inhibition model (Connell and Slatyer, 1977) of succession that states the proximity to a seed source dictates which species will establish first. Species that establish first inhibit other species to establish, except for very tolerant and resistant species. The inhibition model may explain the low richness within the Easton valley due to the seed source on the lateral moraines and only the most tolerant species survive. Furthermore, the low richness in the Easton foreland might also be due to the toxicity of the sulfur flow that occurred in the 1970s, making the soil uninhabitable for certain species. Facilitation may also be driving succession within this foreland, as the species that are present in Zone I and Zone II make the soil and the environment more suitable for other species to develop in Zone III and IV.

Local comparison with the Coleman foreland agrees with these results from the Easton foreland. Dispersal and establishment were found to limit colonization during primary
succession in the Coleman glacier foreland (Jones et al., 2009). In an earlier study, Jones et al.
(2005) studied species richness in the Coleman foreland, and found that overall species richness
increased from early to late succession, with higher counts of species (38/39 species in Zones III
and IV) than were found in the Easton foreland. The slope and aspect in the Coleman valley
create climate conditions similar to the rest of the Pacific Northwest, thus allowing more of the
species from the surrounding (and separate) areas to migrate into the foreland. The Coleman
valley also hosts alder trees, which were not found in the Easton valley. The lack of alders in the
Easton foreland is worth investigating further.

4.5.3 Vegetation Diversity
Richness is the simplest measure of vegetation diversity, but it does not take into account
the relative abundance of each species. The Shannon-Weiner Diversity Index was calculated to
provide additional information about the composition of the Easton community.

Within the Easton foreland, diversity increased in Zones I and II, decreased in Zone III,
and then reached its highest value in Zone IV (Table 4.10). Communities with more species are
considered to be more diverse and the conclusion can be drawn that Zone IV is the most
diverse zone within the foreland. The decrease in Zone III is likely attributed to the lower
number of samples taken in the zone, where \( n = 8 \), driving down the number of individuals
counted; however, overall the diversity values do not change too drastically and stay near a value
of 1-1.5.

| Table 4.10: Shannon-Wiener Diversity Index (H') |
|----------------|----------------|----------------|----------------|----------------|
| Zone 0         | Zone I         | Zone II        | Zone III       | Zone IV        |
| Shannon        |                |                |                |                |
| Diversity H'   |                |                |                |                |
| Zone I         | 1.06           | 1.35           | 0.88           | 1.73           |
| Zone II        |                |                |                |                |
| Zone III       |                |                |                |                |
| Zone IV        |                |                |                |                |
The Shannon-Weiner Diversity Index is useful for comparing diversity of terrain age zones within the Easton foreland and between other forelands. In the Coleman foreland, Shannon Diversity H’ values were slightly higher at 2.08, 1.94, 2.12, 2.23 for Zones I-IV respectively (Jones et al., 2005). This suggests similar species diversity patterns between the Coleman foreland and the Easton Foreland.
Chapter 5. Conclusion

The overall purpose of this study was to create a temporal analysis of vegetation patterns within the Easton foreland and to identify environmental variables influencing vegetation development in a glacier foreland. The main research questions driving this purpose were: How do vegetation cover, richness, and species diversity change through succession? How are vegetation cover, richness, and species diversity related to environmental variables: distance from glacier, elevation, aspect, slope, soil moisture, and photosynthetic active radiation (PAR)? The results from this study provide information that can be used to better understand changes of alpine ecosystems in the future.

The vegetative species found in the Easton foreland are typical of high-alpine communities in the Cascades (Douglas and Bliss, 1977). Each species found in this study has also been noted along the Scott-Paul Trail (Washington Native Plant Society-Plant List). The most abundant species throughout the valley were: *Lupinus polyphyllus, Luetkea pectinata, Tsuga mertensiana*. Most notable was the presence of *Tsuga mertensiana* saplings in Zone I, indicating a relationship to the more developed forest on the surrounding moraines that are likely providing a seed-bank for the valley. Also notable was the lack of alder trees, which was not examined further in this study, but would be worth investigating.

The main conclusion from this study is that vegetation development within the Easton foreland is largely influenced by distance from the glacier, or time since deglaciation. Vegetation begins to establish and develop within 20-40 years of glacial retreat and increases in cover and richness over the next 40-100 years. This pattern can be seen from aerial photographs but this study provides data to support the observed pattern. Distance from the Easton glacier is
exponentially related to vegetation cover, indicating a slow establishment during the ecesis interval (Clements, 1916) from initially after the glacier retreats, and a rapid development from about 40-100 years. This finding reinforces that with increasing distance from the glacier more time has elapsed, allowing for primary succession to reach its mature stages (Matthews, 1992), and determined the rate of change as a logarithmic function. The conclusion that vegetation development is most influenced by a chronosequence in the Easton foreland is supported by other studies (Jones and del Moral, 2005; Moreau et al., 2009) but raises uncertainty about the most appropriate scale of which to apply the geocological framework. Other studies that applied the geocological framework and found variables besides terrain age to most influence vegetation were on much larger scales, temporally and spatially, than this study (Matthews and Whittaker, 1987; Andreis et al., 2001; Rydgren et al., 2014). Before the geocological framework is applied in glacier forelands around the world, the most appropriate scale for the framework needs to be explored. Furthermore, the site-specific context, data-set properties, and statistical methods can influence the outcomes of glacier foreland studies and should be considered when comparing results with other studies (Rydgren et al., 2014). Chronosequences are appropriate for studies on short time-scales, from 0-100 years (Walker et al., 2010), but the effect of terrain age may begin to fade at later ages (Rydgren et al., 2014). This study concludes that the chronosequence framework is acceptable for explaining patterns of primary succession on small temporal and spatial scales and that the geocological framework is scale-dependent.

The most significant limitations of this study are found in the measurements of the environmental variables that change over time. All variables were measured only once during this study and therefore represent an instantaneous condition of the Easton foreland rather than
seasonal conditions. Soil moisture changes seasonally with snow melt, rain events, and summer heat, and may provide more information if it is measured multiple times over the summer season to gather a composite of soil moisture. PAR changes daily and seasonally with the movement of the sun, and solar noon is the most ideal time to measure (Ter-Mikaelian et al., 1999). PAR was not measured at solar noon for each quadrat in the Easton valley due to limitations of time for data collection and the ruggedness of the terrain within the valley. The foreland is a dynamic landscape, and the slope angles of specific locations could change with erosional events. Mostly, these variables were not significantly different among the sites measured in this study, thus are not useful in relation to variation among vegetation. These limitations explain why these variables did not prove to be strongly related to vegetation development at these sites.

An additional limitation, from which many foreland studies suffer, is the uncertainty of terrain age. Refinement of this variable would greatly enhance understanding of patterns of vegetation within this valley. The findings of my study assumed a linear relationship with retreat of the glacier and vegetation development, but glaciers advance and retreat, creating non-linear patterns within the valley as is reflected by the relationship between vegetation cover and distance. Future studies should consider these limitations.

Opportunities for future research are situated at the intersection of the conclusions found by Whelan (2013) and this study to consider the interactions between vegetation and soil. The main finding from Whelan (2013) was that vegetation most significantly impacts soil development. My research provides information about vegetation distribution and confirms that vegetation is beginning to develop in early stages of succession within this foreland, specifically noted in the early establishment of *Tsuga mertensiana*. *Tsuga mertensiana* are shallow rooted with
two-thirds to three-quarters of net primary productivity being allocated below ground (Grier et al., 1985 as cited by Means, 1990). This allocation could be initiating soil development in the early stages, and thus accelerating soil development and vegetation succession. Furthermore, *Tsuga mertensiana* increases acidity in soils by accumulating aluminum in its fine roots, which may accelerate podzolization (Vogt et al., 1987; Means, 1990). Future research should examine the interactions between specific vegetation species and soil development in the Easton foreland to grasp the mechanisms of succession in this foreland and to determine if the early soil and vegetation development is driven by the early establishment of *Tsuga mertensiana*. Relatively few studies have considered the interactions between soil and vegetation (Matthews, 1992).

Further research should also build from this baseline vegetative survey and use this study as a platform for a longitudinal study of the vegetation changes in the Easton foreland. Tracking the vegetation development over longer periods of time will provide a deeper understanding of primary succession within this foreland than can be understood from doing a one-time assessment. A longitudinal study would provide evidence of changes in alpine ecosystems during anthropogenic climate change.

Climate change has already brought warmer temperatures to the Easton foreland which are expected to continue impacting the glacier and vegetation within this ecosystem. The Easton glacier experienced significant retreat in 2015 due to high temperature extremes, and is expected to continue to retreat in the near future (Pelto, 2015). The findings from this study suggest that vegetation will continue to develop upslope as the glacier retreats. Certain vegetation species may increase in productivity with higher temperatures and longer growing seasons (Means, 1990; Washington Department of Fish and Wildlife and National Wildlife Federation, 2011). Forests
currently composed of *Tsuga mertensiana* are predicted to increase in productivity (Washington Department of Fish and Wildlife and National Wildlife Federation, 2011). Radial growth of tree rings in *Tsuga mertensiana* are positively correlated with higher temperatures and negatively correlated with precipitation (Heikkinen, 1985; Graumlich et al., 1986). Depending on how changes in climate effect temperature and precipitation regimes, *Tsuga mertensiana* may thrive in high alpine environments rather than disappear. This could result in the expansion of mountain forests that could change the frequency and intensity of disturbance regimes such as wildfires or insect outbreaks (Bach and Price, 2013) and increase the availability of timber resources. Species will react differently to a changing climate due to their individualistic nature, with some species ceasing to exist in glacier forelands entirely (Erschbamer, 2007). Species survival will need to be examined individually and under multiple climate scenarios to accurately understand potential shifts in alpine ecosystems.

Glacier forelands are complex and active systems that provide opportunities to research the resilience of alpine ecosystems throughout glacial disturbances and climatic change. As glaciers around the world continue to retreat, knowing the key variables driving primary succession within glacial forelands provides insight to the availability of ecosystem services in alpine environments in the future.
References


Appendices

Appendix A: Ordination Results

Ordination was performed to graphically display the relationships between independent and dependent variables. Ordination reduces community data to a 2-D dataset, often used for pattern detection (Everitt, 1998), seeking to explain species in terms of their similarities/dissimilarities. Specifically, Canonical Correspondence Analysis (CCA) was performed, which plots species of a community in a space defined by environmental factors (McCune and Grace, 2002). The data for this study did not reduce well, thus it was not included as a main result as false conclusions can come from ordination that does not explain significant variability, but is presented here.

CCA is a constrained ordination technique that is generally preferred for ecological community abundance datasets. This technique maximizes the correlations between species scores and site scores, and constrains these results to be linear along environmental variables (Palmer, 1993). The total explained inertia is a measure of how well species composition is explained by the variables. The total inertia for this analysis is 0.66, the variability explained by these six environmental variables is 20 percent, leaving 80 percent unexplained. The low explanation could be due to the relatively small sample size of 53 sites. This low explanation could also indicate that other environmental variables need to be considered to better explain the variability of species composition. Although the ordination explains a low percentage, interpreting the diagram below can still be quite useful (Ter Braak, 1986).

The triplot diagram produced by CCA analysis can be used to describe patterns of presence/absence of species along environmental gradients. CCA diagrams are rather intuitive to interpret. The results are extracted based on the relatedness of the species based on each
environmental variable. The species are placed along the environmental variables based on the average of the values of the environmental variables at which a particular species occurs (Ter Braak, 1986); thus, the weighted average is the “center” of a species’ distribution along an environmental gradient. Differences in weighted averages among species indicates differences in their distribution along an environmental gradient, from which community composition can be predicted (Ter Braak, 1986). In the plot below, there are not many strong patterns that can be extracted.

Understanding how to interpret relationships on triplots is an important skill for vegetation studies. The green arrows are environmental variables, and arrows that point away from each other are negatively correlated, and arrows the follow the same angle are positively correlated. Values of the environmental variables increase from the origin, and relationships with species can be interpreted along the environmental gradients. *Abies amabilis, Lupinus polyphyllus* and *Tsuga mertensia* are distributed along the variable distance from the glacier. Distance from the glacier is increasing from the origin of the triplot, meaning *Abies amabilis* is likely to be found further from the glacier than *Lupinus polyphyllus* and *Tsuga mertensia*. Aspect is increasing from the origin of the triplot (where +1 is North). *Carex macloviana* stands out in relation to aspect and *Carex macloviana* is most likely to be found in north facing aspects. PAR values are increasing from the origin, with *Juncus drummondii* occurring in sites with intermediate PAR, while *Luetkea pectinata* and *Poa alpina* occur in sites with low PAR and low elevation. Elevation increases from the origin, showing *Phyllocladus empetriformis* occurs in sites with intermediate elevation and PAR.
Lastly, *Saxifraga tolmiei* occurs in sites with steep slope.

*Figure A*: Triplot from CCA of Easton foreland community. Environmental variables represented by green arrows, sites by circles, and species listed by first four letters of the genus and species name.
Appendix B: Cluster Analysis

Anselin’s Local Moran’s I tests the cluster of feature values with similar magnitude. Below are the results for the environmental variables that proved to be non-significant in explaining vegetation cover and richness throughout the Easton valley based on Spearman’s rank-order correlations. The cluster analysis was performed to confirm homogeneity among these variables, which explains why they were not useful in relation to vegetation variables.

Slope shows homogeneity throughout the valley, with a few clusters of low and high values (Figure B.1). A “cluster” indicates the value is higher/lower than the surrounding units. For slope, there are few clusters (two high, and three low). Overall, slope shows no significant clustering throughout the valley.
Soil moisture has few sites with clustering and one low outlier. These sites are on or near the glacier terminus, the main source of moisture. The values at these sites are higher than the surrounding ones. The low outlier indicates that site’s value is lower than the others nearby.

Overall, soil moisture exhibits evenness throughout the entirety of the valley, showing no significant clustering except near the glacier (Figure B.2).
PAR shows high value clustering and one low value outlier in Zone 1, between 2015 and 1990 glacial extents (Figure B.3). These high clustering values are explained by the lack of vegetation in this zone. This trend is shown in the correlation results of PAR being negatively correlated to vegetation cover and richness. The majority of sites show no significant clustering.
Figure B.3: Standard Deviation and Anselin’s Local Moran’s I results for PAR

Aspect shows a few high and low outliers, with one site of high clustering (Figure B.4). These outliers and cluster can be explained by the rocky landscape of the valley that would change the direction of measurement of aspect. Again, the majority of sites show no significant clustering, indicating overall homogeneity throughout the valley.
Figure B.4: Standard Deviation and Anselin’s Local Moran’s I results for Aspect