DIRECT GROWTH RATES OF SECTION RHIZOCARPON LICHENS IN THE
CASCADE RANGE OF WASHINGTON AND NORTHERN OREGON

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Geography

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ABSTRACT

Between 2002 and 2010, diameters of section Rhizocarpon lichens growing on 11 different surfaces on major volcanoes in the northern Cascades range were observed and measured. Growth rates determined from these direct measurements are between 0.3 and 0.7 mm yr\(^{-1}\) and are consistent with a linear rate of growth determined in other regional studies. Data from this study were both added to and compared with a previously constructed growth curve from the same region. The direct lichen growth observations suggest that: 1) a regionally consistent growth rate averages 0.5 mm yr\(^{-1}\) over a broad geographic range, 2) application of the largest lichen technique provides reliable minimum surface ages despite uncertainties in biological or environmental conditions, and 3) assuming the start of a slow growth phase for lichens near 60 mm in diameter yielded grossly overestimated ages for many ice-contact landforms. This latter point suggests reevaluation of the moraine chronologies developed using poorly constructed lichen growth curves.
Chapter 1
INTRODUCTION

In the Cascade Range of Washington and northern Oregon, many rocky surfaces support section *Rhizocarpon* lichen populations. Over the last four decades, several researchers have applied lichenometric techniques on these landforms to determine both relative and calibrated exposure ages for these surfaces. Most recently, O’Neal and Schoenenberger (2003) used rocky surfaces of known age that support section *Rhizocarpon* lichens to develop a growth curve used to derive numerical ages of lichens in the region. However, their curve, like any other curve that relies on indirect measurements of lichen growth, leaves some doubt regarding the accuracy of growth rate estimates and subsequently derived numeric ages. This study aims to use direct measurement of lichen diameters over time to calculate a growth rate which can be used to ease doubts about the accuracy of indirectly created regional growth curves.

Lichenometric dating techniques are based on the observation that various crustose lichens rapidly colonize freshly exposed rocky surfaces and grow in a slow, radial manner, so that their diameters monotonically increase with age. To derive numeric ages from lichen diameters, the growth rate of lichens must be determined,
using either direct measurement of individual lichen diameters over time or by indirect measurements based on lichen diameters from surfaces of known age.

Obtaining reliable direct measurements of lichen growth requires several years to decades of monitoring, a period beyond the scope of most research projects (Locke et al., 1979). Therefore, many applications of lichenometric dating rely on growth curves developed from indirect measurements that can be completed within a few field seasons. The worldwide development of growth curves over the last five decades has allowed further refinement of simple indirect growth curves by statistical analyses of diameters of lichen populations (Cooley et al., 2006), increasing both measurement accuracy and number of control points (Bradwell, 2001), or re-measuring lichen diameters from previously studied surfaces in subsequent decades (O'Neal and Schoenenberger, 2003). Although each of these approaches provides some level of scientific merit for improving a growth curve, none are statistically comparable to the growth-rate data that can be obtained via repeated annual to decadal observations of individual lichens. Moreover, observed variability in annual growth rates, caused by both intrinsic biological and local environmental factors, has led to considerable debate regarding the development, accuracy, and application of indirect growth curves (Armstrong, 2005).

In this study we evaluate direct growth rates based on 35 measurements of 11 *Rhizocarpon* section lichens growing on different surfaces in the Cascade Range of
Washington and northern Oregon. Because all of these surfaces have been used for control points in previously developed indirect growth curves, the results of this study provide a unique opportunity to: 1) compare the growth rates from both direct and indirect methods, 2) evaluate the potential loss of original colonizers in the indirect curves, 3) identify changes in the growth rates of lichens over time, and 4) more accurately determine the rate of regional growth using several datasets covering a broad geographic range. The value in these results is largely that growth curves are very useful for dating surfaces that are of climatic significance such as ages of moraines marking Little Ice Age glacier terminal positions throughout the study area (i.e., Laroque and Smith, 2004; Koch, 2007).
Chapter 2
BACKGROUND

2.1 Lichenometry as a Dating Technique

Lichenometry as a rock exposure dating technique was first introduced by Beschel (1958) to date boulders deposited along past ice margin positions. This technique operates under two primary assumptions: 1) Lichen colonization occurs rapidly after fresh rocky surfaces are exposed. 2) Lichen growth is radial such that larger diameters indicate longer exposure times of rocky surfaces. Although Beschel's pioneering work with the European Alps and Greenland moraines proved critical in developing an age-diameter relationship, lichenometry as a viable numeric-dating technique requires a growth curve based on knowledge of actual time since substrate exposure where lichens are being measured.

Beschel's introductory work spurred efforts to generate insight into lichen growth rates in a variety of locations (Armstrong, 1983; Benedict, 2008; Locke et al, 1979; Beschel, 1973). This subsequent research identified that a variety of unknown and variable environmental parameters such as temperature, precipitation, and elevation control lichen growth rates in various locations. It became clear that the
technique would require insight into the rate of lichen growth at each study site to account for the environmental conditions of that area.

In situations where individual lichen diameters can be monitored over long periods, direct lichen growth rates can be calculated. However, section *Rhizocarpon* lichens grow slowly, so a directly measured growth rate takes several years to decades to obtain. However, small changes in climatic factors such as average temperature, sun exposure, and precipitation can affect lichen growth (Locke et al, 1979). Because lichens are poikilohydric organisms, long-term increases in precipitation and relative humidity can result in short-term anomalous growth rates and create an anomaly (Armstrong, 2005). Microclimatic observations may be needed to determine anomalous localized effects on lichen growth rates.

### 2.2 Growth Curve Development

Lichens are a symbiotic relationship between a fungus and a photosynthetic partner, usually a green algae (Noller and Locke, 2000). Lichens are commonly categorized into two categories, crustose and foliose. Foliose lichens have a leaf-like structure and are not relevant to the type of analysis discussed in this thesis. The section *Rhizocarpon* lichens used in this study are crustose and literally grow like a crust on a surface. They have no vertical structure, tissues, or distinct parts, and their
body, or thallus, tends to grow in a circular in shape (Haput, 1953; Noller and Locke, 2000).

Modeling crustose lichen growth is difficult due to their slow growth rates and the variety of unknown environmental factors that can influence lichen growth (Armstrong and Bradwell, 2010). Because there is no globally applicable model, researchers often rely on indirect evidence of lichen growth based on a plot of the time since substrate stabilization as a dependent variable and thallus diameter as the independent variable. This indirect method of determining lichen growth rates obviously relies on thalli measurements from substrates of known age. Beschel called the indirect approach the "method of the dated substrate" (Beschel, 1958). This relationship showing change in thallus diameter over time is expressed as the radial growth rate (RGR) (Calkin and Ellis, 1980). The shape of the RGR curve expresses the nature of lichen growth in the region. A linear RGR indicates steady growth, while curvature shows either growth acceleration or deceleration.

The shapes of growth curves have long been thought to reflect three different stages of lichen growth past colonization. The initial phase is a period of rapid growth where RGR increases to a maximum (see Armstrong, 1983 or Innes, 1983 for a description of growth phases). This phase is characterized by a curvature in the growth curve. A linear-growth phase follows the more rapid initial growth phase. During the linear-growth phase, thalli generally attain a diameter greater than 30 mm
(Armstrong, 1983; Armstrong and Bradwell, 2010). The linear-growth phase is expressed by a flattening growth curve demonstrating a slowing rate of growth. A decreasing, or senescent phase is the final phase of lichen growth and is generally observed in lichen thalli with diameters greater than 50 mm (Armstrong, 1983; Armstrong and Bradwell, 2010). During this phase, growth rates begin to decrease and the growth curve may actually begin to slope downward.

Growth curves based on indirect measurements of lichen growth can be established without respect to monitoring the direct measurements of individual lichens. Such a growth curve can be readily used to determine the age of a landform of interest in the same region and at similar elevations to the calibration sites. Growth curves generated from the indirect relationship between lichen diameters and surfaces of known age has provided an invaluable method for determining the exposure ages of many late Holocene landforms and bedrock surfaces where other established dating techniques such as radio carbon dating and dendrochronology are not applicable (e.g. Miller, 1969; Fuller, 1980; Burke, 1972; Burbank, 1981; Lillquist, 1988; O’Neal, 2005).

All of the early investigations into the applications of lichenometric dating techniques made the assumption that the largest lichen was the most suitable for use because it was assumed to be the oldest and therefore the best representation of exposure time. However, there were immediate concerns about biological variability
and whether the largest lichen was a merely a biologically anomalous member of the population rather than the first colonizer (see Noller and Locke, 2000). As a result of these concerns, researchers began to utilize statistics of lichen populations to assuage concerns of biological abnormalities. Despite nearly four decades of increasing the complexity of statistical analyses of lichen populations in an attempt to improve the development of lichen growth curves, Armstrong and Bradwell (2010) suggested that the more straightforward techniques generate the most intuitive and accessible results.

Ecesis presents a source of potential error in the accuracy of a growth curve. Ecesis reflects the time it takes for a thallus to establish itself on a substrate and grow large enough to be seen by the naked eye. Ecesis for lichen is not uniform and may vary largely by location (Armstrong and Bradwell, 2010; Locke et al, 1979). This period can be as little as 8 years or be as great as 50 years, depending on the region, and should not be included in the time factor of RGR (e.g., O'Neal and Schoenenberger, 2003). However, ecesis time should be accounted for when dating a landform. Ecesis time is added to the landform age obtained by a RGR.

Statistics of lichen size and frequency data can aid in identifying anomalies. Lichen thalli size distribution on a substrate surface should resemble a log-normal distribution (Locke et al, 1979). A linear regression can be applied to the size-frequency results using thallus diameter as the independent variable and logarithmic
frequency as the dependent variable. This regression will allow anomalous thalli to be easily identified as outliers of the regression (Locke et al, 1979).

2.3 Data Analysis Procedures

After establishing an RGR, lichenometric dating typically follows one of four established approaches: 1) the largest lichen technique, 2) the average of the largest five lichens, 3) the size-frequency approach, and 4) fixed-area largest lichen (FALL) technique. Beschel originally pioneered the largest lichen approach in which the diameter of the single largest lichen of one species growing on a surface is measured (Bradwell, 2009). Beschel hypothesized that the size of the single largest thallus growing on a surface could give an estimate for time since substrate exposure (Beschel, 1961). If the largest lichen were an anomalous reflection of favorable microclimatic conditions rather than an accurate representation of elapsed time since substrate exposure, a growth curve generated from its radius may not accurately date a substrate. The largest five lichens theory was developed in the 1970s, wherein the five largest lichen diameters on a substrate within a fixed area are averaged to avoid placing too much significance on any outlier (Locke et al, 1979). The mean of the largest five lichen diameters is then used to calibrate a growth curve. Some projects choose to take more than the five largest lichens on a surface, however doing so has not been shown to improve accuracy (Bradwell, 2009).
A survey of all lichens growing on a surface is often unrealistic for very large landforms with abundant lichens. Thus, the largest lichen or the largest five lichen methods are often applied within a representative sample area, generally between 25 m$^2$ and 500 m$^2$, depending on the size of the surface being dated (Bradwell, 2010). Growth curves generated using the largest lichen or the largest five lichen methods within a fixed surface area cannot be compared directly to curves generated from using the same two methods applied to an entire landform because of the difference in surface sizes. In most cases, using the largest lichen or the largest five lichen methods within a fixed study area can be justified, as long as the techniques used are consistent throughout the study (Bradwell, 2009).

The size-frequency approach takes into account the longest axis of all thalli of a particular species growing in a sample area, typically between 25 m$^2$ and 50 m$^2$, and should include at least 1000 thalli (Bradwell, 2009). The size-frequency approach was originally employed to distinguish different types of anomalous thalli growing on a single surface, but it has also been successfully used as a dating technique (Innes, 1983; Bradwell, 2004). In addition to generating a growth curve, the size-frequency approach can be used to determine important environmental factors that have an effect on growth rates, such as snow-kill frequency, substrate stability, and micro-environmental tolerance.
The fixed-area largest lichen (FALL) method developed out of the largest lichen and five largest lichen approach. The single largest lichen from one species within a sample area is measured. Each sample area is relatively small (about 1 m²), but generally includes hundreds to thousands of sample areas (i.e., Bull and Brandon, 1998; Lowell et al., 2005). Statistical treatment is then applied to determine a surface age. This method was originally developed to determine ages in areas where there may be more than one exposure age such as rock falls (Bradwell, 2009). The lichen cover approach presumes that the percentage of substrate surface covered by lichen will increase over time, so the total area covered by lichen on a surface is recorded (Bradwell, 2009). The FALL method is generally only used when one of the three previously mentioned (largest lichen, average of largest five lichens, percent cover) is either not possible or highly impractical because it is the most subjective of the four outlined dating methods (Bull and Brandon, 1998).

Recently, more advanced statistical treatments such as the Generalized Extreme Value (GEV) approach and the U² approach have been applied to lichenometric dating studies (Karlen and Black 2002; Jomelli et al., 2008). The GEV approach assumes that an outlier exists somewhere outside of the data set and is typically applied when researchers suspect the oldest lichens have not been located. The Generalized Extreme Value approach is more traditionally applied to problems where extensive data sets representing frequency distribution are available. The U² treatment is a method by which two samples sets are tested to see how much they
vary. Typically, these more advanced statistics are applied in studies with no control points. The GEV and U2 approaches are used to develop a curve by attempting to estimate the ages of old lichens which could not be located. These treatments are extremely complex, and have not yet been shown to provide more precise and accurate dating information than any of the four traditional approaches (Bradwell, 2009).

2.4 Applications of Lichenometry

Lichenometry is widely used as a landform dating technique within the climatic geomorphology community. However, it is worth noting that lichen growth curves have been successfully applied as a dating technique in a number of fields. The lichenometric dating of stone surfaces and structure at archaeological sites throughout North America, Europe, and New Zealand has proved useful in providing numeric ages where other techniques often fail (e.g., Broadbent and Bergqvist, 1986 and Benedict, 2009). Bull and Brandon (1998) used the fixed-area largest lichen technique to determine numeric ages of earthquake and rock fall events in New Zealand’s Southern Alps. More recently, Armstrong (2004) purports that lichenometry has useful applications in the context of climate change evaluation for reliably dating climatically sensitive landscapes.
Chapter 3
STUDY AREA

All data presented in thesis were collected from sites on Mount Baker, Mount Rainier, Mount Adams, and Mount Hood in the Cascade Mountain Range of Washington State and northern Oregon between 48° 18’N and 45° 36’N, and between 121° 59’W and 121° 8’W (Figure 1). All sites were selected for this study because they are locations where Porter (1981), O’Neal and Schoenenberger (2003), or O’Neal (2005) previously collected lichenometric data, and they continued to host lichens suitable for measurement throughout the study period. Data were collected from rocky surfaces that were either 1) natural andesitic or granodiorite outcrops and boulders, or 2) human-made structures that were constructed from the aforementioned stone. All lichen-bearing surfaces used in this study had little or no direct vegetation competition which would have potentially affected lichen growth rates.

At Mount Baker (Figure 2), lichen diameters were measured on an andesitic rock wall and boulder (Figure 3) in the south facing Easton Glacier foreland at elevations between 1280 m and 1290 m. The boulder was deposited along the margin circa A.D. 1910 (Thomas, 1997; O’Neal, 2005). Similarly, the adjacent rock wall
where lichens were measured was exposed at the same time by Easton Glacier’s retreat.

All sites where lichen measurements were collected at Mount Rainier (Figure 4) are located on the mountain’s southern flank and within Mount Rainier National Park. The elevation of study sites at Mount Rainier ranged from 1195 m to 1655 m. Lichen data were collected from naturally occurring rocky surfaces as well as human-made structures. The federal government established Mount Rainier National Park in A.D. 1889. The older structures in the park are of a similar age to many natural surfaces that are of geomorphic and climatic significance. The Park Service built these structures at a time when the mountain could not be easily accessed from outside areas, so the buildings and structures within the park were made out of local andesite and granodiorite. These structures provide an excellent source for growth curve calibration. Dating glacier forelands is one of lichenometery’s primary applications, and these structures are located at the same elevation and built out of the same rocky material found in glacier forelands on the mountain. However, unlike many glacial landforms, the precise age of these structures is on record.

Mount Rainier National Park is the only location within the study area where lichen diameters were measured on human-made structures. The Park Service cleaned lichen bearing surfaces at the Narada Falls comfort station and the gas station at Sunrise where Porter (1981) had collected lichenometric data. As of August 2010, the
Park Service had not removed datable lichens from the other man-made structures subsequently used by O’Neal and Schonenberger (2003).

The southern part of the study area included two sites on lateral moraines of the Adams Glacier on the northwest slope of Mount Adams (Figure 5) and Eliot Glacier on the north-facing flank of Mount Hood at an elevation of 1820 m (Figure 6). Some encroachment of some small vegetation was noted on the Eliot Glacier moraine, similar to that noted by O’Neal and Schoenenberger (2003) when revisiting the Kautz Creek site described by Porter (1981). As in that case, it is likely that lichens will yield to more complex vegetation types in coming years.
Chapter 4

FIELD METHODS

At each location, the lichen(s) measured by O’Neal and Schoenenberger (2003) or O’Neal (2005) were located for this study. However, to be included in this thesis, thalli were required to be: 1) either circular or nearly circular shape, 2) uninhibited by competing adjacent lichens, 3.) growing at an altitude between 1195 m and 1825 m, and 4) growing on exposed, stable andesite or granodiorite rock surfaces without nearby dense vegetation cover. After meeting these criteria, the diameter of the largest circle that could be inscribed within each thallus measured using digital calipers with an accuracy of ±0.02 mm. Note that the diameter was reported to the nearest tenth of a millimeter.

The intervals between subsequent measurements for each of the 11 lichens range from 1 to 8 years, and depended on access to these sites related to other research projects during the study period. At Mount Baker, lichen diameters were measured on a glacially scoured rock wall and boulder in the Easton Glacier foreland in A.D. 2002, 2007, 2009, and 2010. The lichen diameters measured on surfaces at Mount Rainier include: 1) a large boulder on the left lateral moraine of the Nisqually Glacier foreland in A.D. 2002, 2007, and 2010, (Figure 7) 2) the Sunbeam Creek Bridge in A.D. 2002, 2007, and 2010, 3) the Edith Creek foot bridge in A.D. 2002 and 2010 (Figure 8), 4)
the guardrail at Rickseeker Point in A.D. 2002, 2007, and 2010 (Figure 9), 5) the guardrail at Inspiration point in A.D. 2002, 2007, and 2010 (Figure 10) 6) the rocky foundation of Paradise Lodge in A.D. 2002, 2007, and 2010 (Figure 11).

The single lichens measured at Mounts Hood and Adams, respectively, are from boulders in moraines in the foreland of the Eliot Glacier in A.D. 2002 and 2010 (Figure 12), and in the foreland of the Adams Glacier (Figure 13) in A.D. 2003, 2006, and 2007. All boulders used in this study are greater than 2 m in diameter, thereby providing a stable surface for lichen growth. We acknowledge that O’Neal and Schoenenberger (2003) collected lichen measurements on surfaces where the exposure age was constrained using maps, photos, historical accounts, dendrochronology, and tephrochronology. Such constraints were not provided for the exposure age of the boulder used from the Adams Glacier foreland by O’Neal (2005). However, this does not affect the evaluation of growth rates at that location where the boulder is in a stable position at the toe of a 60 m tall moraine (O’Neal, 2006).
Chapter 5

LAB METHODS

5.1 Growth Rates

Lichen diameter data are used to directly calculate growth rates at each site for each measurement interval. Individual lichen growth rates were calculated as the change in lichen diameter over the time since the previous measurement. The growth rate for each interval was multiplied by the total number of years in that interval, added together, and then divided by the total number of years in the study to obtain a weighted-average growth rate. This weighed average allows for the calculation of a regionally averaged growth rate, and standard deviation, which accounts for the uneven measurement intervals at different sites.

5.2 Growth Curves

The lichen-diameter data are used to generate a growth curve plotted as an age versus diameter relationship between lichen diameter and surface age for a particular region. Typically, lichenometric studies present data as scatter plot where a statistical fit of the data is presented. Porter (1981) and O’Neal and Schoenenberger (2003) used a linear regression in their growth curves for the Cascade Range (Figure 14).
All lichen diameters collected since 2002 were added to the growth curve created by O’Neal and Schoenenberger in 2003 (Figure 15). This growth curve places surface age in years on the X axis and lichen diameter in millimeters on the Y axis. This study includes diameter and age data from those previous studies, so each of the 11 thalli appear in the revised growth curve more than once. A linear regression was used to maintain continuity with the 2003 curve so that a meaningful comparison between the 2003 curve and the revised 2010 curve could be made. The 95% prediction interval is also included in this revised growth curve. The slope of this curve is an indirectly calculated growth rate because it shows a change in diameter with time that does not track individual lichens along each period. This curve allows for changes in rates of lichen growth to be evaluated over time as their diameters increase. The multiple appearances of each thallus illustrate how individual diameters change with age.

We generated a scatter plot of lichen diameter versus year measured (Figure 16). Each point on the scatter plot represents the diameter of an individual lichen thallus at a specific measurement date. Each of the 11 thalli used in this study was given a unique symbol. This notation allows for a quick, visual assessment of the growth rates of individual thalli throughout the region. The growth rates for each of the 11 lichen thalli are constant as illustrated by the linear relationship between data points on this scatter plot. Finally, a graph was constructed showing the individual
growth rates for each of the 11 *Rhizocarpon* section lichens from the different study locations (Figure 17).
Chapter 6

RESULTS

The raw data for the 20 lichen observations taken at 11 sites between 2002 and 2010 are presented for this study are presented in Table 1. The data collected in 1976 by Porter (1981) are also presented in Table 1 for comparison. Table 2 shows the growth rate in mm yr\(^{-1}\) for each measurement interval at each site. The growth rates for each interval for the entire data set range from 0.3 mm yr\(^{-1}\) to 0.7 mm yr\(^{-1}\) and resemble a normal frequency distribution. Three sites had a growth rate of 0.3 mm yr\(^{-1}\) for a measurement interval. Six sites thalli had growth rates of 0.4 mm yr\(^{-1}\) for a measurement interval. Five lichens had a growth rate of 0.5 mm yr\(^{-1}\) for a measurement interval. Six lichens grew at 0.6 mm yr\(^{-1}\) for an interval, and only one interval at one site had a growth rate of 0.7 mm yr\(^{-1}\). The majority of lichens are growing at rates between 0.4 mm yr\(^{-1}\) and 0.6 mm yr\(^{-1}\), which are rates within one standard deviation of the mean. Only four measurement intervals out of twenty saw growth rates outside of this range. Visual analyses of these data do not suggest that lichen age correlates with either the lower or higher limits of the growth rates observed. The weighted average growth rate in Table 2 accounts for the uneven time intervals between the 35 measurements and was calculated to be 0.5 mm yr\(^{-1}\) with a standard deviation of 0.1 mm yr\(^{-1}\).
A linear trend fit through the age vs. diameter dataset of 35 measurements collected between A.D. 2002 and 2010 has an $r^2$ of 0.97 and a slope of 0.45. Similarly, a linear trend fit through these data with those of Porter (1981) and O’Neal and Schoenenber (2003) has an $r^2$ of 0.97 and a slope of 0.44 (Figure 15). Adding the 2010 data to the 2003 growth curve does not yield significant changes in the slope of the curve. These two graphs illustrate that growth rates of various aged lichens have remained nearly constant since at least 1976, despite previous depictions of slower growth rates for older lichens.

The average growth rate for the lichen on the Adams Glacier moraine was 0.3 mm yr$^{-1}$ between A.D. 2003 and 2006, and 0.6 mm yr$^{-1}$ between A.D. 2007 and 2008. While growth was slow between A.D. 2003 and 2006, the weighted average growth rate at the Adams moraine was 0.4 mm yr$^{-1}$ between A.D. 2003 and 2008, which is one standard deviation away from the mean average weighted growth rate for this study. At the Eliot Glacier Moraine on Mount Hood, the average growth rate and the weighted average growth rate between A.D. 2002 and 2010 is 0.3 mm yr$^{-1}$. This is the slowest rate of growth in the study, however the Eliot glacier site had the highest amount of potentially competing vegetation.

At Mount Baker, the average growth rates for *Rhizocarpon* between A.D. 2002 and 2010 at both the boulder and the rock wall sites at the Easton Glacier moraine were 0.5 mm yr$^{-1}$ and 0.4 mm yr$^{-1}$ respectively. The weighted average growth
rate for the boulder site is 0.6 mm yr\(^{-1}\), and the weighted average growth rate at the rock wall is 0.5 mm yr\(^{-1}\). Table 1 shows that the size of the lichen on the boulder is nearly identical in size to the size of the lichen on the rock wall. These sites are nearly adjacent and the same age, so their similar lichen sizes and rates of growth make sense. The average growth rate for the rock wall behind the fee station was calculated to be 0.2 mm yr\(^{-1}\) between A.D. 2002 and 2008. During the same time interval, the weighted average growth rate for the fee station was calculated as 0.2 mm yr\(^{-1}\).

At the Nisqually Glacier Moraine the average growth rate between A.D. 2002 and 2010 was 0.4 mm yr\(^{-1}\) and the weighted average growth rate was calculated to be 0.5 mm yr\(^{-1}\). This is the oldest lichen included in this study and it is growing at rates that fall within one standard deviation of the mean growth rate for the entire study. Therefore, it does not appear to be slowing in growth despite its age and large size. The average growth rate and the weighted average growth rate for Paradise Lodge from A.D. 2002 to 2010 was 0.6 mm yr\(^{-1}\). The average growth rate and the weighted average growth rate at Edith Creek Bridge between A.D. 2002 and 2010 were calculated as 0.5 mm yr\(^{-1}\). The guardrail at Inspiration Point had an average growth rate and a weighted average growth rate of 0.5 mm yr\(^{-1}\) between A.D. 2002 and 2010.

The average growth rate for the guardrail at Rickseeker Point was calculated as 0.5 mm yr\(^{-1}\) between A.D. 2002 and 2010, and the weighted average
growth rate for the same time interval was calculated as $0.5 \text{ mm yr}^{-1}$. The average growth rate for the Sunbeam Creek Bridge between A.D. 2002 and 2010 was $0.4 \text{ mm yr}^{-1}$ and the weighted average growth rate was calculated to be $0.4 \text{ mm yr}^{-1}$. The directly calculated rates of growth for the lichens growing on Park Service structures is extremely useful for dating the natural surfaces in the region because park service records tell the exact age of the lichen bearing structures. Knowing an exact relationship between surface age and rate of lichen growth allows for more accurate dating of natural landforms whose exact exposure time is unknown.
CHAPTER 7

DISCUSSION

Our direct measurements of 11 Rhizocarpon section lichens in the Cascade Range of Washington and northern Oregon suggests that growth is steady for lichens between 20 and 160 years in age. These rates fall within the range of growth rates identified in other indirectly developed curves from this region (i.e., Porter, 1981; O'Neal and Schoenenberger, 2003, McCarthy, 2003). However, the 0.5 mm yr\(^{-1}\) growth rates presented herein failed to identify any reduced growth in lichen with thallus diameters greater than 60 mm as suggested in these previous studies. This growth rate indicates that caution should be exercised when attempting to identify the timing of senescence in the study region (e.g. Bradwell and Armstrong, 2007). The weighted average growth rate of 0.5 mm yr\(^{-1}\) presented in this study is 0.1 mm yr\(^{-1}\) larger than that presented by O’Neal and Scheonenberger (2003).

Despite the consistency in our results with previous growth curves for the study region, results from a 6-year study by Armstrong (2005) for the Steven’s Pass area of Washington identified much slower section Rhizocarpon growth rates of 0.07 mm yr\(^{-1}\). If these data are indicative of a regional growth rate, those applying lichenometric dating techniques to landforms in the Cascades over the last four
decades have been measuring diameters of fused lichens on Little Ice Age landforms (see Bradwell, 2010 for a description of this problem). Given the large number of lichen measurements collected throughout the Cascades since the 1960's that fit within the expectations of previously published growth curves (e.g. Miller, 1967 and 1969; Burke, 1972; Fuller, 1980; Lillquist, 1988; Porter, 1981; Burbank, 1981), it is unlikely that every researcher has made the same measurement errors. A more plausible explanation for the slow growth rates would be that the size-age relationships can be dramatically affected by local environmental conditions at individual study sites (e.g. O’Neal 2010; Laroque and smith, 2004).

Precisely identifying the relationship between climatic characteristics temperature, precipitation, and relative humidity is difficult in terms of their impacts on lichen colonization and growth in the Cascades. Three major climatic forcings influence the climate of this study area in the north Cascades. Semi-Permanent high and low pressure systems over the northern Pacific Ocean contribute to seasonal rainfall patterns (PRISM, 2011). The summer months experience the least precipitation while the winter months generally have the most precipitation as a result of a seasonal high-pressure center off the coast of Canada over the northern Pacific Ocean (PRISM, 2011). Proximity to the Pacific Ocean gives the study area a moderate climate compared to other locations at similar latitudes. The Pacific Ocean also generates a supply of moist air, which often results in significant orographic precipitation on the windward side of the Cascade Range. O’Neal (2010) indicates that
lichens suitable for dating growing in the study area must lie within a well defined range of suitable environmental parameter that includes more than 80 cm of annual precipitation, granodiorite or andesitic surfaces, low amounts of competing vegetation, and locations below the average annual snow line.

Since its development as a surface exposure dating technique, many studies have emphasized potential sources of error in growth curve development due to intrinsic variability from biological or environmental controls. Despite the general curvature that characterizes growth curves from the broader earth science community, general knowledge of lichen growth rates confirms that lichenometry is a fundamentally sound approach where the signal exceeds both natural noise and user errors. Thus, we offer the growth rate for use in the Cascade Range with several caveats. First, there are indeed local environments within our study area where the growth curve may not yield accurate results (see the examples in O'Neal, 2010 and Laroque and Smith, 2004). Second, to apply largest lichen techniques, we argue that all lichens growing on a landform must be observed and compared to the largest five on the surface to ensure that it is not an extreme outlier or coalesced lichens. Although we appreciate the value of statistical treatments of large populations of lichens for predicting extreme values (i.e., predicting the size of missing old lichens), many landforms in the Cascades are in historically and currently active erosional areas and sustain a statistically insufficient lichen population on a few large boulders.
The directly calculated growth rate of 0.5 mm yr\(^{-1}\) indicates that linear growth phases depicted by both the Porter (1981) and O’Neal and Schoenenberger (2003) growth curves proceeds at slightly more rapid rate. Adding the lichen data from this thesis to the previous growth-curve datasets does not improve this problem and yields a similarly underestimated growth rate of 0.4 mm yr\(^{-1}\) (Figure 15). This result suggests that previous growth curves were developed without respect to original colonizers on older landforms allowing for a false depiction of a slow-growth phase for the larger lichens identified in previous studies (i.e., data from the older Nisqually moraines). For the observed period between 20 and 160 years, it appears that the rate of growth in the study area remains constant (see Figure 16). Thus, until more data are collected regarding direct growth rates, the range and standard deviation for directly calculated growth rates are better indicators of error than the previously asserted 95% prediction intervals on the 2003 growth curve (Figure 14).
REFERENCES


O'Neal, M.A., 2006. The Effects of Slope degradation on lichen on lichenometric dating of Little Ice Age moraines. Quaternary Geochronology 1, 121-128.


Figure 1. Shaded relief map of western Washington and Oregon showing the locations of the major Cascades volcanoes where lichen data were collected (Modified from O’Neal and Schoenenberger, 2003).
Figure 2. Study site locations in the Easton moraine, Mount Baker, Washington State.
Figure 3. Photograph of lichen data collection in the Easton glacier foreland.
Figure 4. Map of the study sites located on the southern side of Mount Rainier, Mount Rainier National Park, Washington.
Figure 5. Map of the study site location on the Adams glacier moraine, Mount Adams, Washington.
Figure 6. Map of the study site location on the north-facing Eliot glacier moraine, Mount Hood, Oregon.
Figure 7. Photograph of lichen data collection on a boulder from the Nisqually glacier left lateral moraine, Mount Rainier National Park, Washington.
Figure 8. Measuring lichens on the Edith Creek Bridge foundation, Mount Rainier National Park, Washington.
Figure 9. Photograph of the guardrail from Rickseker Point from which lichen data were collected, Mount Rainier National Park, Washington.
Figure 10. Photograph of the guardrail at Inspiration Pont from which lichen data were collected, Mount Rainier National Park, Washington.
Figure 11. Lichen bearing rocks from the Paradise Lodge foundation, Mount Rainier National Park, Washington.
Figure 12. Photograph of the Eliot Glacier right-lateral moraine, Mt. Hood, Oregon.
Figure 13. Photograph of the left lateral moraine in the Adams Glacier foreland, Mount Adams, Washington.
Figure 14. Section *Rhizocarpon* growth curve (O’Neal and Schoenenberger, 2003).
Figure 15. Section *Rhizocarpon* growth curve for the Cascade Range of Washington and northern Oregon using a total of 6 control points from Porter (1981), O’Neal and Schoenenberger (2003), O’Neal (2005), and data collected for this study. The black line represents a linear regression with the dashed lines depicting the 95% prediction interval.

\[ y = 0.4422x + 1.7536 \]

\[ R^2 = 0.97018 \]
Figure 16. Graph displaying the year measured vs. diameters of the 11 *Rhizocarpon* section lichens from different study locations in the Cascade Range of Washington and northern Oregon.
Figure 17. Graph displaying the individual growth rates for each of the 11 *Rhizocarpon* section lichens from the different study locations in the Cascade Range of Washington and northern Oregon. The interval in years is presented in each circle and the average is presented as a black line.
Table 1. Year measured, substrate age when measured, and thallus diameter for all observations included in this study.

<table>
<thead>
<tr>
<th>Location</th>
<th>Site</th>
<th>Year Measured(A.D.)</th>
<th>Substrate Age When Measured (years)</th>
<th>Thallus Diameter (mm)</th>
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<tr>
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<td></td>
<td>2009</td>
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<td>54.0</td>
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<tr>
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<td></td>
<td>2010</td>
<td>110</td>
<td>54.4</td>
</tr>
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<td></td>
<td>2002</td>
<td>86</td>
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<td></td>
<td>2010</td>
<td>94</td>
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<td>56</td>
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<td></td>
<td>2010</td>
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<td>2010</td>
<td>64</td>
<td>24.1</td>
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Table 2. Years measured, interval between measurements, and growth rates for each site on all four peaks used in this study.

<table>
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<tr>
<th>Location</th>
<th>Site</th>
<th>Years Measured</th>
<th>Interval (years)</th>
<th>Growth Rate (mm yr⁻¹)</th>
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<td>rock wall between fee station and challet</td>
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