National Park Service
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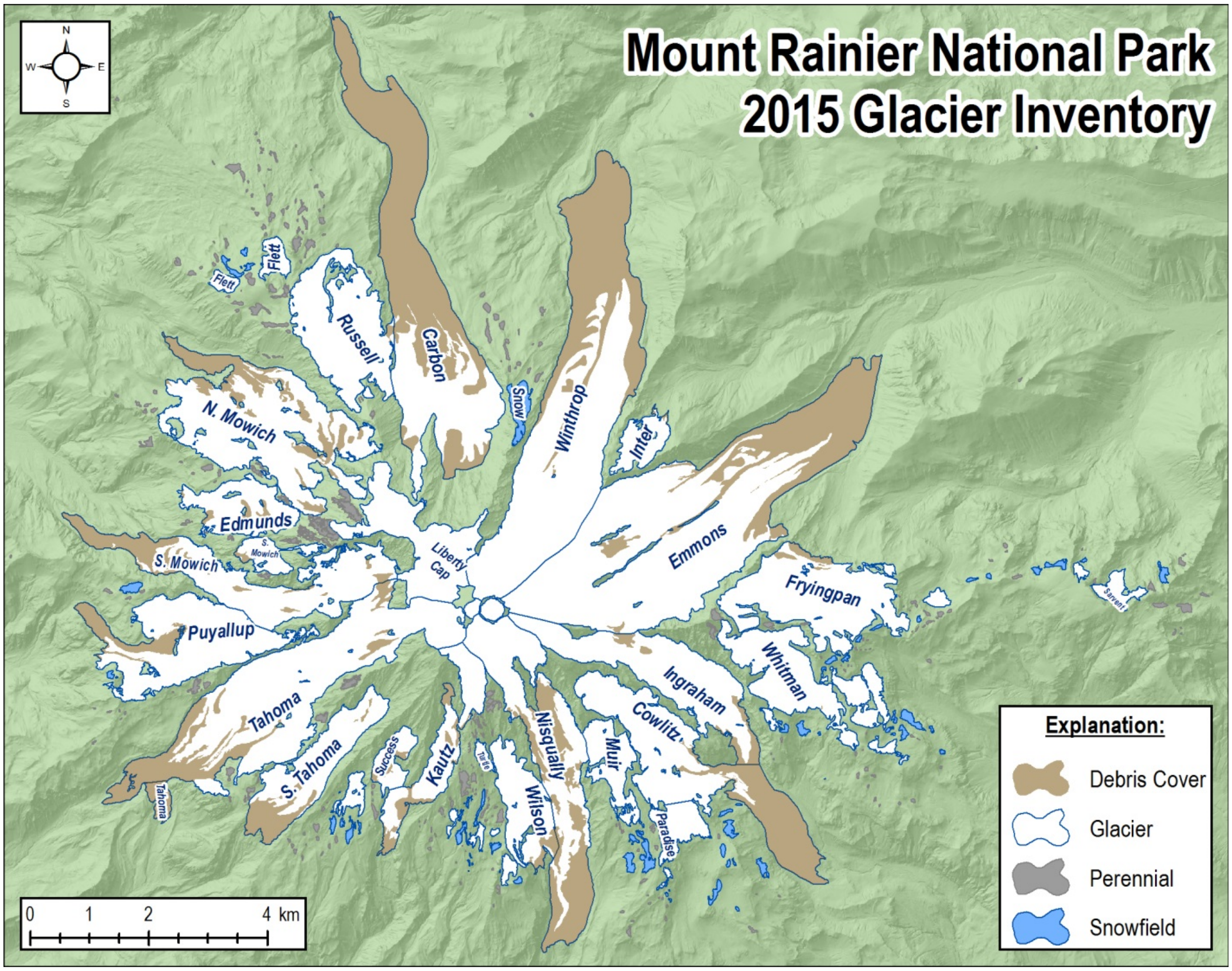
Natural Resource Stewardship and Science

Change in Glacial Extent at Mount Rainier National Park from 1896 to 2015

Natural Resource Report NPS/MORA/NRR—2017/1472



ON THIS PAGE
Extents of perennial snow, snowfields, and glaciers on Mount Rainier in 2015 from this study
Courtesy of the National Park Service

ON THE COVER
Oblique aerial photo of the south face of Mount Rainier showing the Kautz, Success, Van Trump, Wilson, and Nisqually Glaciers. Photo taken 11/28/2015 at 5:00 PM.
Photograph courtesy of Michael Gauthier and used with expressed permission.

Change in Glacial Extent at Mount Rainier National Park from 1896 to 2015

Natural Resource Report NPS/MORA/NRR—2017/1472

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U.S. Department of the Interior
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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data. Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

This report is available in digital format from the Mount Rainier National Park website and the Natural Resource Publications Management website. To receive this report in a format that is optimized to be accessible using screen readers for the visually or cognitively impaired, please email irma@nps.gov.

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Plate 1: 2015 glacier ice and debris cover extent, Mount Rainier National Park

Plate 2: Change in glacier extent, 1896 to 2015, Mount Rainier National Park

Conversion Factors

Multiply	by	to obtain
meter (m)	3.28084	foot (ft)
meter (m)	1.09361	yard (yd)
meter (m)	1,000	kilometer (km)
kilometer (km)	0.62137	mile (mi)
square meter (m^2)	10.76391	square foot (ft^2)
square meter (m^2)	1.19599	square yard (yd^2)
square meter (m^2)	0.000001 ($1x10^{-6}$)	square kilometer (km^2)
square kilometer (km^2)	0.38610	square mile (mi^2)
square kilometer (km^2)	247.10538	acre (ac)
cubic meter (m^3)	35.31467	cubic foot (ft^3)
cubic meter (m^3)	1.30795	cubic yard (yd^3)
cubic meter (m^3)	0.000000001 ($1x10^{-9}$)	cubic kilometer (km^3)
cubic kilometer (km^3)	0.23991	cubic mile (mi^3)
cubic kilometer (km^3)	810,714	acre-feet (ac ft)

Glossary

Ablation – The opposite of accumulation; refers to all processes (evaporation, sublimation, melting, erosive removal of snow by wind, and calving) that remove snow, ice, or water from a glacier or snowfield.

Crevasse – A deep open crack in glacial ice due to differential movement of parts of the glacier over uneven topography at the base of the glacier.

Feature – A point, line, or polygon that represents a single item within a feature class.

Feature class – A homogeneous collection of common features, each having the same spatial representation, such as points, lines or polygons and a common set of attribute columns.

Feature vertices – A geometric point consisting of X (Easting or Longitude), Y (Northing or Latitude) and, optionally, Z (elevation) coordinates that represents a single location within a line or polygon that is used to construct a larger feature. For example, a square would have four feature vertices – one at each corner. Larger polygons can have many more feature vertices.

Firn – Partially compacted granular snow or ice that has been left over from past seasons in an intermediate stage and density between fresh snowfall and glacier ice.

Glacier – In this study, refers to a large, slowly moving mass or river of ice formed by the compaction of snow in areas where snowfall exceeds snow ablation. Glaciers show evidence of movement via crevasses, ogives, and other flow features.

Multispectral – Operating in or involving several regions of the electromagnetic spectrum. In remote sensing, a multispectral image can be thought of as an archive that has several subset images within it, each appearing at different frequencies in the electromagnetic spectrum.

Ogive – In a glacial setting, alternating bands of light and dark (or debris-covered) ice that form on some glaciers, sometimes below icefalls. Glacial ice flows faster at the center of the glacier, which forms ridged arcs of ice that bend downstream.

Panchromatic – Sensitive to all visible colors of the spectrum. Panchromatic images are created when a satellite imaging sensor is sensitive to a wide range of wavelengths of light, typically spanning a large part of the visible part of the electromagnetic spectrum.

Perennial snow – In this study, refers to a small (generally less than 4,000 m^2 [1 acre]) patch of snow or firn accumulation which lies on the surface longer than other seasonal snow cover, generally persisting longer than two years.

Snowfield – In this study, refers to a permanent patch of snow or firn accumulation. Snowfields are generally larger than perennial snow patches. Some larger snowfields can show some signs of downhill movement (e.g., crevasses).

Stereo-pair – An image that contains two views of a scene side-by-side. These images can be viewed by a human eye (one image for the left eye, one for the right) or analyzed by computer software. When properly viewed, the pair will create a three-dimensional image. Computer software can extract relative elevations from the stereo-pair.

Abstract

Surface area extents of glacial ice and perennial snow within Mount Rainier National Park were delineated based on 2015 aerial and satellite imagery to study glacier changes. These extents were compared with previously completed databases from 1896, 1913, 1971, 1994, and 2009. Mapped extents include areas of debris-covered stagnant ice present in the terminal regions of many glaciers at Mount Rainier. Additionally, any snow patches noted in satellite-acquired aerial images as of September 30, 2015 were considered to be perennial snow.

In 2015, Mount Rainier National Park contained a total of 29 named glaciers which covered a total of 78.76 ±1.11 km^2 (30.41 ±0.43 mi^2). Perennial snowfields added another 2.06 ±0.12 km^2 (0.80 ±0.05 mi^2), bringing the total perennial snow and glacier cover within the park as of 2015 to 80.82 ±1.11 km^2 (31.21 ±0.43 mi^2). The total area of debris cover on glaciers at Mount Rainier is 20.01 ±0.42 km^2 (7.73 ±0.16 mi^2), or approximately 25.4% of mapped glaciers. The largest glacier at Mount Rainier was the Emmons Glacier, which encompasses 11.03 ±0.58 km^2 (4.26 ±0.22 mi^2). The Carbon Glacier, the third largest glacier in the park at 7.26 ±0.39 km^2 (2.80 ±0.15 mi^2), had the largest area of debris cover at 4.84 ±0.27 km^2 (1.87 ±0.11 mi^2), covering 66.7% of its area.

The change in glacial and perennial ice surface area from 1896 to 2015 was -52.08 km^2 (-20.11 mi^2), a total reduction of 39.1%. This corresponds to an average rate of -0.44 km^2 per year (-0.17 $mi^2 \times yr^{-1}$) during the 119 year period. Recent changes (between the 6-year period of 2009 to 2015) showed a reduction of -1.46 km^2 (-0.56 mi^2) of glacial surface area, or a 1.8% reduction in glacial area and a rate that corresponded to -0.24 km^2 per year (-0.09 $mi^2 \times yr^{-1}$).

Overall, this data shows a gradual loss of ice extent at Mount Rainier. A gradual loss of ice is significant because a loss of ice area can represent a major glacial volume change. Changes in glacial volume were not calculated in this study but that rate can be extrapolated based on work by other authors. If the regional climate continues to change in ways that shrinks glacial extent, further loss in surface area park-wide is anticipated, as well as the complete loss of lower-elevation small glaciers with surface areas less than 0.2 km^2 (0.08 mi^2) in the next few decades.

Acknowledgements

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Introduction

Glaciers are an important geologic, geomorphic, biologic and aquatic resource at Mount Rainier National Park (MORA). The presence of glaciers on Mount Rainier not only shapes the edifice, but provides a year-round source of water for aquatic ecosystems in the park. Glaciers also provide insight into the climate of temperate alpine regions and studying the change in glaciers over time can illustrate the impacts of climate change in the region (Meier 1998). Glacier surfaces can respond immediately to accumulation and ablation of snow and ice, but it may take decades to centuries for the glacier's extents to respond (Bahr et al. 1998).

Glaciers at Mount Rainier also have been the source for damaging outburst floods during the park's history. The Nisqually, Kautz, South Tahoma, Van Trump, and Winthrop Glaciers at MORA have all unleashed outburst floods since the 1950s (Copeland 2009). These floods are not caused by failure of ice-dammed lakes or geothermal heating, but by warm temperatures or rainfall events (Hoblitt et al. 1998). These glacial outburst floods can quickly mobilize into debris flows due to an overabundance of loose, unstable sediment at steep glacial margins. Such outburst floods and debris flows have impacted park infrastructure and have led to changes in park management in large swaths at MORA (Walder and Driedger 1994).

Monitoring the health of glaciers can be complicated but is necessary to address the topic of how climate change will affect park resources in the future. Glaciers are an important indicator of climate change because the physical changes that occur in glaciers provide visible evidence of changes in temperature and precipitation (US EPA 2016). At present, glacial monitoring at MORA encompasses the following study efforts: 1) Mass balance; 2) surface elevations; 3) volume; and 4) surface area extents. Mass balance studies have been conducted on the Nisqually and Emmons Glaciers at MORA since 2003 as part of the North Coast and Cascades Inventory and Monitoring Network (NCCN I&M) as one of a dozen major vital signs for region parks (Riedel and Larrabee 2015; Hoffman et al. 2014; National Park Service 2014; National Park Service 2012; Riedel et al. 2010). Surface elevation studies on the Nisqually Glacier have been surveyed yearly since the 1930s, but are aerially limited due to the time and staffing constraints in conducting such studies (Heliker et al. 1983). Volume estimation is problematic due to the physical limitations of glaciers (i.e., being able to accurately determine the topography of the bed), but have been accomplished in the past (e.g., Driedger and Kennard 1986). Surface area extents are relatively straightforward and easy to obtain for a large area based on aerial imagery.

This study documents changes in surface area extents for glaciers and perennial snowfields at MORA. This study builds on extents of glaciers acquired in 1896, 1913, 1971, 1994, and 2009 (Robinson et al. 2010; Nylen 2001; Matthes 1913; Russell 1898). The 2015 season was an ideal year to study the changes in glacial extent due to a remarkably low snow year (National Park Service 2015) and presence of clear, high-resolution (<0.5 m/pixel) satellite- and airborne-acquired aerial imagery which allowed the delineation of glaciers, snowfields and perennial snow patch features.

This work compliments other recent studies on glacial loss in the Cascade Range, including volcanoes like Mount Adams (Sitts et al. 2010), Mount Baker (Pelto 2015), Mount Hood (Ellinger

2010) and glaciers within Olympic National Park (Riedel et al. 2015) and North Cascades National Park (Riedel and Larrabee 2016; Dick 2013; Pelto 2008; Granshaw and Fountain 2006). Nearly all glaciers in the Cascade Range are retreating and thinning, with a notable exception of the Crater Glacier at Mount St. Helens, which has advanced due to emplacement of a lava dome during an eruptive period between 2004 and 2008 (Walder et al. 2010). For example, between 1904 and 2006, the area of glacial ice on Mount Adams has decreased by 49% (from 31.5 km^2 [12.2 mi^2] to 16.2 km^2 [6.3 mi^2]) (Sitts et al. 2010). In the Olympic Mountains in 2015, 184 alpine glaciers had a combined area of 30.2 ±0.95 km^2 (11.7 ±0.37 mi^2), but have had a 34% decrease in combined area since 1980 (Riedel et al. 2015). The volume loss for the glaciers in the Olympic Mountains has been estimated at 17-24% in the 26 year period between 1987 and 2010.

In the North Cascades, combined glacier area in the Skagit River basin has decreased by 32.02 ±1.60 km^2 (12.36 ±0.62 mi^2), or a 19% decrease from 1959-2016 (Riedel and Larrabee 2016). Glaciers in the North Cascades as a whole have seen some of the most drastic retreats in the entire region. Between 1900 and 2009, the glacial area in the North Cascades as a whole decreased from 533.89 ±22.77 km^2 (206.14 ±8.79 mi^2) to 236.20 ±12.60 km^2 (91.20 ±4.86 mi^2), or a total area loss of approximately 56% (Dick 2013). Dick (2013) notes that century-scale loss is associated with increasing regional temperatures in winter and summer and that the precipitation record shows no statistically significant trend. Loss of glacial area and associated volume loss of glacial ice represents a significant loss of freshwater resources in the region, which can have compounding ecologic effects (Riedel and Larrabee 2016; Riedel et al. 2015).

Study Area

Mount Rainier is 4,392 m (14,410 ft) stratovolcano located approximately 70 km (45 mi) southeast of Tacoma, Washington (Figure 1). Mount Rainier is the tallest mountain in Washington State and has more glaciers and perennial ice than all other Cascade Volcanoes combined (Driedger and Kennard 1986) and about a quarter of the total ice area in the lower 48 states (Meier 1998). Given its proximity to the Pacific Ocean, prevailing westerly winds, and significant topographic prominence, Mount Rainier is a substantial orographic barrier. Moisture heading in-land hits this orographic barrier and tremendous precipitation falls over the mountain as rain and snow. At higher elevations, years of snowfall accumulate and do not melt out, which eventually form glaciers.

Glaciers at Mount Rainier vary considerably in size, altitude, and aspect. Those glaciers on the north aspect of Mount Rainier are generally larger and have more volume (Driedger and Kennard 1986). Glaciers are present at altitudes between 1,100 m (3,600 ft) and 4,392 m (14,410 ft) and occupy positions on all aspects of the volcano. Glaciers and perennial snow fields account for approximately 8.5% of the total area of Mount Rainier National Park.

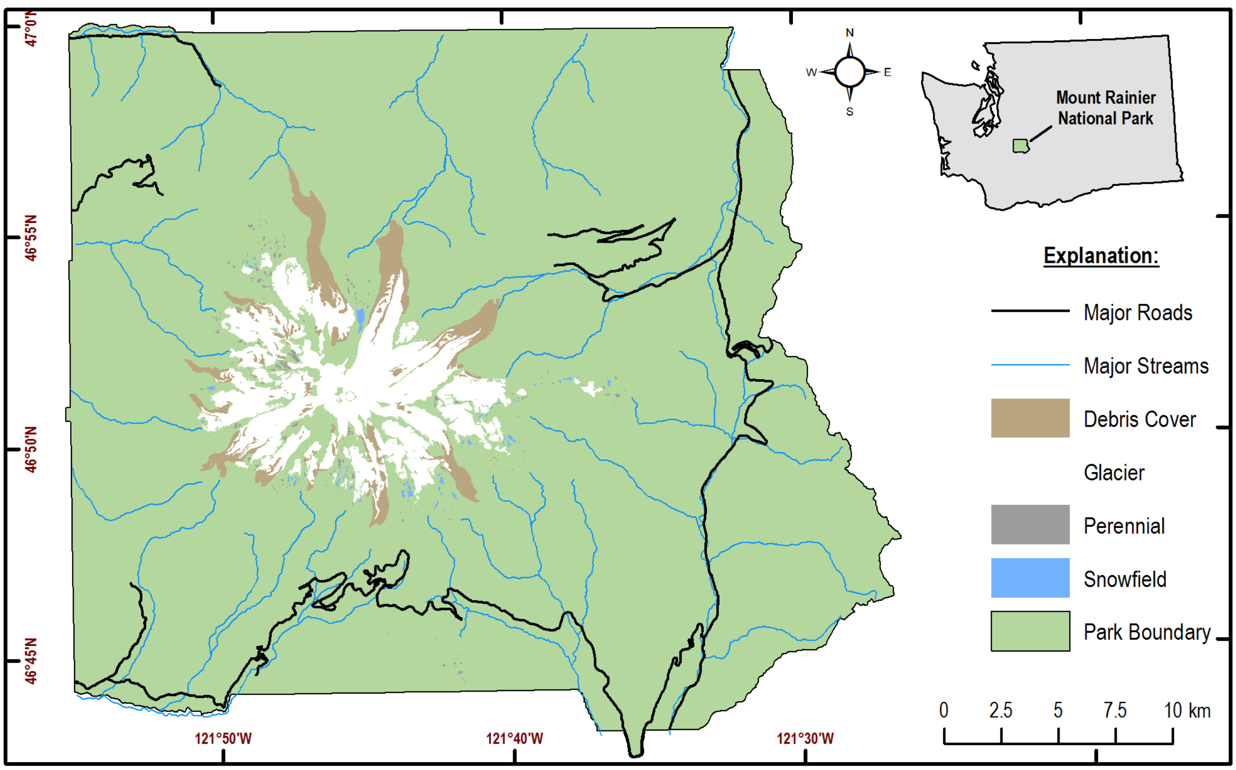

Figure 1. Mount Rainier National Park extent and study area.

Previous Research

Glacier extents have been mapped several times over the last 120 years at Mount Rainier. While individual glaciers were mapped prior to the 1890s, the first dataset available for the entire park was completed in 1896 (Russell, 1898). Follow-up mapping for park-wide glaciers occurred in 1913, 1971, and 1994 (Nylen 2001; Matthes 1913). A digitized map of park glaciers and perennial snowfields was completed following a LiDAR survey in 2007/2008 and was probably the highest resolution map available to date (Robinson et al., 2010). These maps all serve to provide evidence of temporal changes to the surficial extents of glaciers at Mount Rainier over time.

The older datasets (e.g., 1896 and 1913) had poor spatial accuracy and areas that appeared to not match up with observed topographic features. For example, some features in the 1896 inventory show glaciers which cross over topographic breaks and boundaries between glaciers that do not match with modern mapping. These data were included as it provided an important and historic data point for trends in glacial change at the park, despite the potential perceived mapping errors. Additionally, some previous data sets did not map areas of known stagnant ice within their glacial boundaries. For example, on the lower Winthrop Glacier, a large area of debris-covered stagnant ice is present at the lower terminal margins of the glacier. Some inventories excluded this area or did not map the entire stagnant body as a glacier. The current inventory mapped known stagnant areas, which could slightly change current glacial extents.

Methods

Glacier extents (2015) and comparison with previous inventories

Mapping of 2015 glacial extents in this study was completed by hand digitizing features from aerial imagery at a 1:1,000 scale. Each polygon was mapped based on the appearance of sharp glacial boundaries from aerial images. In situations where boundaries were not clearly observable, professional judgement was used and results were compared with previous inventories. Observable features that assisted with the mapping in aerial photos included surface streams that originated from beneath glacial ice, wet supraglacial debris, crevasses, and others. Consistency was maintained with previous glacial extent data sets with regard to adjacent glaciers that shared a common boundary. Field verification was undertaken in locations were possible, but due to the large aerial expanse of this inventory, field verification was not completed for all glaciers. When completed, 69,507 feature vertices were created for 512 features in this glacier extent feature class and 15,517 feature vertices were created for 20 features in the debris extent feature class.

A total of three aerial image sets were acquired and analyzed for this study (Table 1; Figure 2). The primary image product used in this study was panchromatic satellite photography acquired from the WorldView-2 (WV2) satellite. The WV2 satellite is a commercial Earth observation satellite owned and operated by DigitalGlobe and provides both panchromatic and multispectral imagery. These images have been acquired as stereo-pairs, which are used in other studies to calculate mass balance of glaciers in the park (Shean 2017). Distinct delineation of glacial boundaries is possible because of the high resolution of the data (< 0.5 m per pixel). WV2 images in some areas were clipped or had cloud cover and required other imagery to complete the glacial delineation. In these instances, the USDA Forest Service's (USFS) National Agriculture Imagery Program (NAIP) products were used. NAIP images capture "leaf on" aerial imagery during the peak growing season with the goal to collect 1-meter images for the entire conterminous United States (USDA 2015). NAIP images are generally collected once a year, every other year for each state (e.g., Washington will be collected again in 2017).

Table 1. Image data sources acquired and analyzed for this study. See Figure 2 for map of coverage.

Date	Source	X-Resolution	Y-Resolution	Area of Image (km^2)	Coverage area of Park
07/29/2015	NAIP	1.00 m	1.00 m	952.306	100%
09/11/2015	WV2	0.35 m	0.50 m	210.795	22.1%
09/30/2015	WV2	0.25 m	0.35 m	322.324	33.8%

The more recent images were preferred for mapping, as it more accurately reflected the extent of glacial and perennial features through or at the end of the ablation season than older images. If a feature extended off of the youngest (09/30/2015) image, then the next older image (09/11/2015) was used to map the feature. If the feature of interest was not on either of the two youngest images, then the 07/29/2015 NAIP image was used to map the feature. This was the case for some of the glaciers and perennial snow fields in the southern part of the park (e.g., Sarvent Glaciers and snow fields in the Tatoosh Mountains).

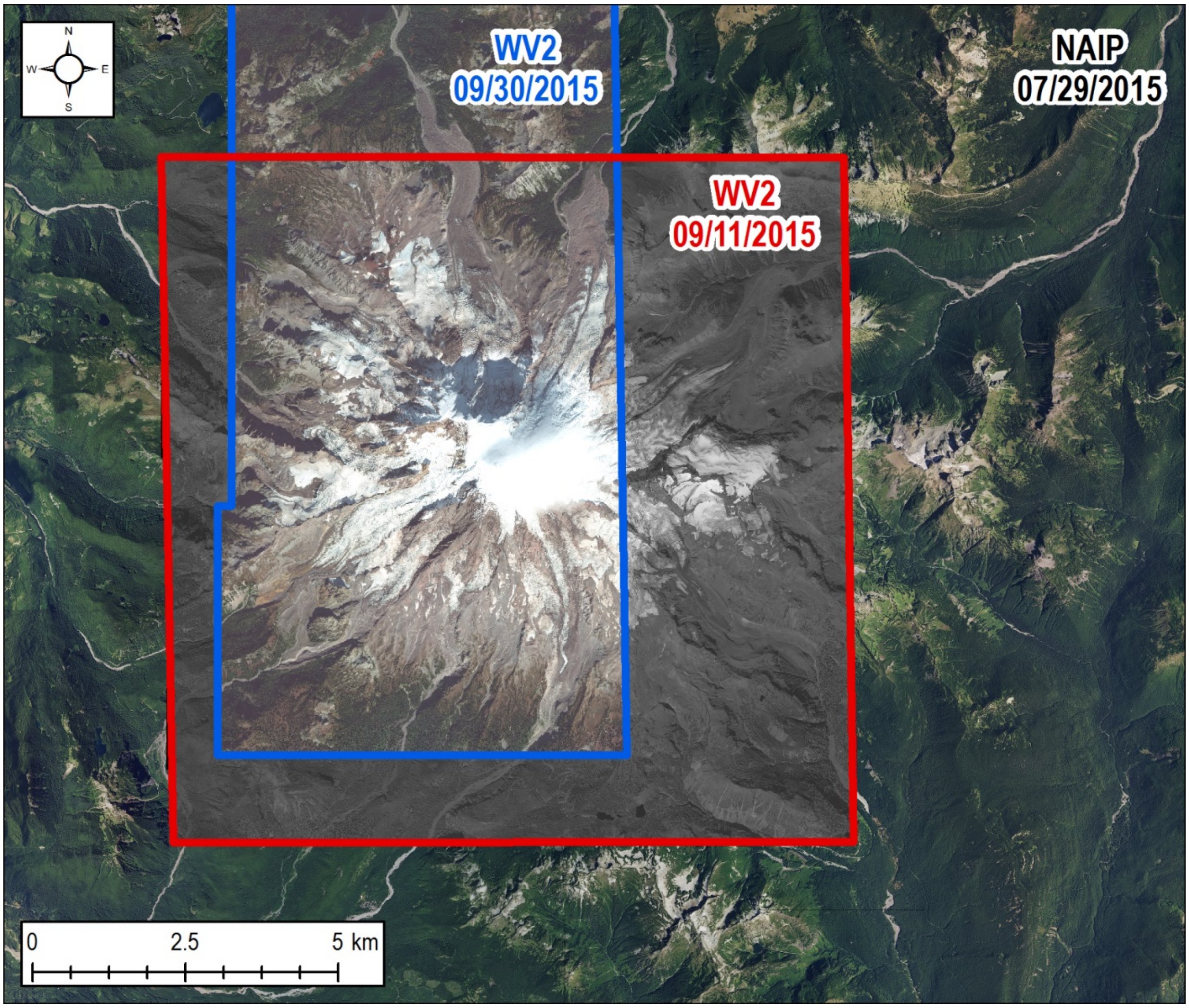

Figure 2. Extent and dates of data sources used in mapping of glacial extents for the 2015 season.

Each mapped glacial or perennial feature also included attribute information. This information includes: (1) Id - Auto incrementing identification field; (2) ShortName – Short name for the feature, useful in small-scale maps (e.g., "S. Tahoma"); (3) FullName – Full name for the feature, useful in large-scale maps (e.g., "South Tahoma Glacier"); (4) FeatType – Enumerated value that indicates the type of feature, which can be: Glacier, Perennial, Snow field; (5) Watershed – The larger watershed that the feature drains to; (6) Area_m2 – Area of the feature in square meters; (7) Area_ft2 – Area of the feature in square feet; (8) Source – Image data source for the mapping (Table 1); (9) HasCrevasse – Integer that states if the feature has crevasses (1) or does not (0); (10) LinkedID – A field that helps link individual shapes to a larger parent glacier (for example, if one glacier has separate parts but has a common linked id, displaying the larger glacier system is easily done by selecting common linked ids from the definition query); and (11) EditedBy – A small text field to indicate who last edited the feature.

Some previous datasets have listed separate glaciers as "glacial systems". For example, the 2009 inventory included the Nisqually and Wilson (Nisqually-Wilson), Cowlitz and Ingraham (Cowlitz-

Ingraham), Kautz and Success (Kautz-Success), and Paradise and Stevens (Paradise-Stevens) Glaciers together instead of separate glaciers. Additionally, the 1898 inventory only lists the Cowlitz Glacier and does not name the Ingraham Glacier as its own name. In order to compare the 2015 data with previous inventories, those glaciers in glacial systems have been added together – all individual glaciers now have their own feature or features. Topographic information from the 2007/2008 park LiDAR dataset was used to help identify topographic breaks that were used to delineate ice divides between glacial systems.

This study mapped the extents of glacial ice and debris at MORA. Estimates of ice volume were not made, however. Others have surveyed ice volumes of the park (e.g., Driedger and Kennard 1986). This study facilities park updates for estimate ice volume in the future.

The 2015 glacier extents GIS layers for MORA are available from the park or through the National Park Service Integrated Resource Management Application Data Store website at: https://irma.nps.gov/DataStore/Reference/Profile/2240011.

Debris cover in 2015

Many of the large glaciers at Mount Rainier have significant areas of debris cover. Debris cover on a glacier can reduce ablation which can lead to decreased glacial retreat, especially in the lower areas of the glaciers ablation zones (Collier et al. 2015; Lambrecht et al. 2011; Kayastha et al. 2000). The Emmons Glacier is an excellent example of how debris cover can retard glacial recession rates. The Lower Emmons received a thick deposit of rock debris on top of the glacial ice during a large rockfall event off of Little Tahoma Peak in 1963 (Crandell and Fahnestock 1965). This rock fall led to both a glacial advance and later, a slowing of glacial recession during a timeframe when other glaciers in the park were all retreating. Current research into debris cover on the Emmons Glacier shows a measured decrease in ablation rates in areas with higher debris cover (Riedel and Larrabee 2015; Dits and Moore 2013), a trend that has been shown in the other studies across the globe.

Debris cover accumulates on glaciers at Mount Rainier from a variety of sources: rock fall, wind-blown sediment, and medial moraine deposits (Crandell and Fahnestock 1965). In order to better understand temporal changes to debris cover at Mount Rainier, debris on glaciers was mapped in 2015.

Debris mapping on glaciers turned out to be more complex than initially thought. Due to the nature of debris on the glacier, a progression of clear, debris-free glacial ice to complete debris cover can exist, and defining the point when “debris begins” is less than straightforward. In order to accomplish this mapping, a lower resolution (1:5,000) was used, which makes the boundary less accurate, but easier to visualize when digitizing. This data was used only as a rough boundary of glacial debris and can be corrected by viewing the data at higher resolutions.

Errors and accuracy of 2015 inventory

Manually digitizing glacial boundaries inherently introduces error into final measurements. These errors include: 1) resolution and accuracy of the background image, 2) the accuracy and precision of placed vertices along glacial margins, 3) position uncertainty among debris- and non-debris-covered glaciers, and 4) natural variability of glaciers from year to year. Imagery errors depend on the source of the image. For example, Worldview 2 satellite images have a horizontal position error (CE90 – Circular Error, 90% percentile) of approximately 5 m (16 ft) (DigitalGlobe 2016), whereas NAIP images impose a standard that 95% of well-defined points tested fall within 6 m (20 ft) of true ground points (Eckert 2011). Horizontal accuracy of vertices placed along glacier margins are a function of the scale of the map created and can be quantified by using standards employed by the United States Geological Survey's National Mapping Program standards (USGS 2017). Such standards state the following: "horizontal accuracy as 90% of all measurable points must be within 1/30th of an inch for maps at a scale of 1:20,000 or larger." For the purposes of this study, the horizontal accuracy of a point at 1:1,000 scale is 0.847 m (2.778 ft) and 1:5000 scale is 4.233 m (13.889 ft) based off of the USGS nomenclature.

Total surface area error, E, is therefore expressed as a combination of total measurable uncertainty, E_1, along with potential variability error, E_2. Total measurable uncertainty, E_1, is defined by Carisio (2012) as:

$$E_1 = \sqrt{A_i} \times (p + u) \times \sqrt{2}$$

Where A_i is the surface area of the delineated glacier, p is the horizontal uncertainty of the source image, and u is the horizontal uncertainty of a placed point. Potential variability error, E_2, can vary as little as 2% and as much as 5% for glaciers in question; generally, smaller glaciers have a higher variability error (Riedel and Larrabee 2016; Riedel et al. 2015; Sitts et al. 2010; Post et al. 1971). For the purposes of this study, and to account for all other potential errors, a relatively high 5% value was used for potential variability error:

$$E_2 = 0.05A_i$$

Total surface area error, E, is therefore calculated as the following:

$$E = E_1 + E_2$$

Current Glacier Statistics

Bare earth LiDAR for the entire park (Watershed Sciences 2009) was clipped to each delineated glacier (as of 2015) to determine maximum and minimum elevations for each glacier. Total relief is calculated as the range between minimum and maximum elevations for a particular glacier. The length of the glacier was determined by drawing a line from the most upstream to most downstream point on each glacier, while attempting to follow any curves or bends in the glacier at the middle of the feature. Average slope was calculated using the "Slope" tool in Arc Toolbox within ArcMap 10.3 (ESRI, 2016). Slope was calculated in degrees and identifies the maximum change in z-value (elevation) from each cell in a raster surface.

Average flow direction was calculated using ArcMap's "Flow Direction" tool. Flow direction is often used for hydrologic networks, and is used to show the flow direction from each cell in a raster dataset to its next steepest downslope neighbor (ESRI 2016). Averaging all the cells for a delineated glacier provides insight into the direction the glacier flows toward. The flow direction raster dataset for the park was previously calculated for stream network analysis by taking the 2007/8 bare earth LiDAR layer and “filling” it to correct for sinks and other small imperfections in the data (ESRI 2016). Flow direction was then run for the entire park using the filled layer as the input. Once the 2015 glacier extent layer was delineated, individual glacier features were extracted from the Flow Direction layer by using the “Extract by Mask” tool. This left a raster layer with flow directions for each cell. The average flow direction for each glacier, $\bar{\alpha}$, was calculated using the following formula:

$$\bar{\alpha} = \text{atan2}\left(\frac{1}{n}\cdot\sum_{j=1}^{n}\sin\alpha_j\,,\frac{1}{n}\cdot\sum_{j=1}^{n}\cos\alpha_j\right)$$

Where α_j is the flow direction for each of the n cells in the raster dataset. An R script was written to calculate the flow direction with inputs from the raster dataset. The flow direction indicates the direction the glacier flows toward, both in degrees (where 0° is true north) and a textual description of the heading (e.g., NNW = North-northwest). It should be noted that the flow direction tool is designed primarily for surface water streams and not for glaciers. The intent with this use is to identify the average flow direction of the glacier. Variation can and likely does exist that could change the results noted in this study due to the complex flow patterns in glaciers due to sliding and ice deformation.

Results

2015 Glacier Extents

Glaciers at Mount Rainier in 2015 varied in size from 0.03 km^2 (0.01 mi^2) to 11.03 km^2 (4.26 mi^2) and averaged 2.79 km^2 (1.08 mi^2) (Figure 3; Table 2). Five glaciers had surface areas greater than 5 km^2 (1.93 mi^2) while 12 glaciers had a surface area less than 1.5 km^2 (0.58 mi^2); the remainder of the park glaciers (12) had a surface area between 1.5 km^2 and 5 km^2 (0.58 mi^2 and 1.93 mi^2). Unnamed perennial ice and snowfields (405 mapped features) had a total area of 2.06 ±0.12 km^2 (0.80 ±0.05 mi^2). A map of individual glaciers is shown in Appendix A. A smaller scale map showing the entire park is attached as Plate 1.

The total area of named glaciers at Mount Rainier in 2015 was 78.76 ±1.11 km^2 (30.41 ±0.43 mi^2) (Table 2). Adding in unnamed perennial ice and snowfields, the total volume of year-round snow and ice at Mount Rainier was 80.82 ±1.12 km^2 (31.21 ±0.43 mi^2).

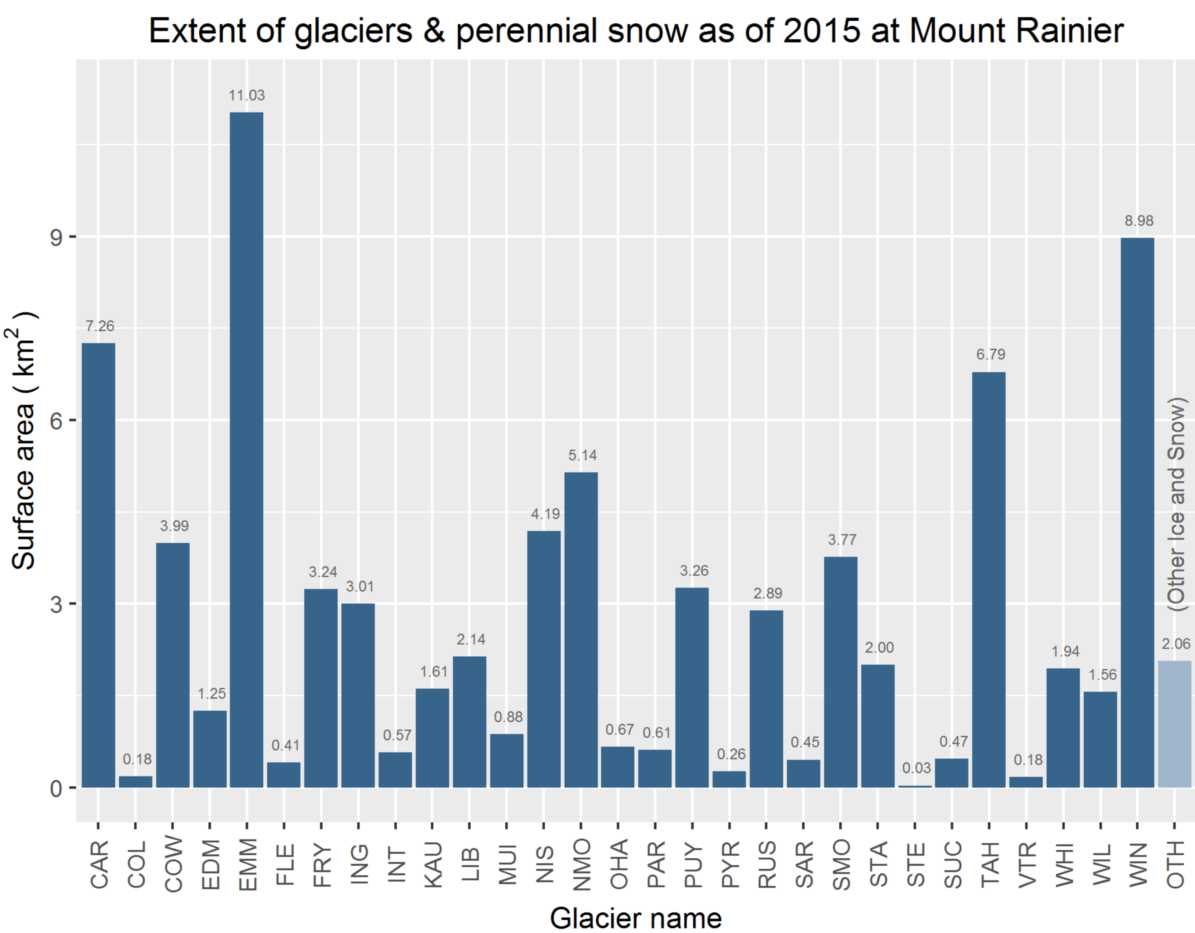

Figure 3. Extent of perennial snow and glaciers at Mount Rainier in 2015, based on data in Table 2. The value at the top of each column is the total surface extent of each glacier. Glacier name identification can be found in Table 2.

Table 2. Extent of glacial ice, snowfields, and perennial snow in 2015 at Mount Rainier.

Glacier name	Ident	Rank	m^2	km^2	mi^2
Carbon Glacier	CAR	3	7,256,844 ±362,842	7.257 ±0.385	2.802 ±0.149
Columbia Crest Glacier	COL	27	180,346 ±9,017	0.180 ±0.013	0.070 ±0.005
Cowlitz Glacier	COW	7	3,990,333 ±199,517	3.990 ±0.216	1.541 ±0.083
Edmunds Glacier	EDM	18	1,252,436 ±62,622	1.252 ±0.072	0.484 ±0.028
Emmons Glacier	EMM	1	11,027,125 ±551,356	11.027 ±0.579	4.258 ±0.223
Flett Glaciers	FLE	25	405,650 ±20,283	0.406 ±0.026	0.157 ±0.010
Fryingpan Glacier	FRY	10	3,244,565 ±162,228	3.245 ±0.177	1.253 ±0.068
Ingraham Glacier	ING	11	3,007,289 ±150,364	3.007 ±0.165	1.161 ±0.064
Inter Glacier	INT	22	573,974 ±28,699	0.574 ±0.035	0.222 ±0.013
Kautz Glacier	KAU	16	1,611,015 ±80,551	1.611 ±0.091	0.622 ±0.035
Liberty Cap Glacier	LIB	13	2,138,709 ±106,935	2.139 ±0.119	0.826 ±0.046
Muir Snowfield	MUI	19	875,186 ±43,759	0.875 ±0.051	0.338 ±0.020
Nisqually Glacier	NIS	6	4,191,616 ±209,581	4.192 ±0.227	1.618 ±0.087
North Mowich Glacier	NMO	5	5,144,280 ±257,214	5.144 ±0.276	1.986 ±0.107
Ohanapecosh Glacier	OHA	20	668,974 ±33,449	0.669 ±0.040	0.258 ±0.016
Paradise Glacier	PAR	21	611,832 ±30,592	0.612 ±0.037	0.236 ±0.014
Puyallup Glacier	PUY	9	3,257,836 ±162,892	3.258 ±0.178	1.258 ±0.069
Pyramid Glacier	PYR	26	262,231 ±13,112	0.262 ±0.017	0.101 ±0.007
Russell Glacier	RUS	12	2,892,409 ±144,620	2.892 ±0.159	1.117 ±0.061
Sarvent Glaciers	SAR	24	454,659 ±22,733	0.455 ±0.029	0.176 ±0.011
South Mowich Glacier	SMO	8	3,765,553 ±188,278	3.766 ±0.204	1.454 ±0.079
South Tahoma Glacier	STA	14	2,001,825 ±100,091	2.002 ±0.112	0.773 ±0.043
Stevens Glacier	STE	29	33,139 ±1,657	0.033 ±0.003	0.013 ±0.001
Success Glacier	SUC	23	469,850 ±23,493	0.470 ±0.029	0.181 ±0.011
Tahoma Glacier	TAH	4	6,787,052 ±339,353	6.787 ±0.361	2.620 ±0.139
Van Trump Glaciers	VTR	28	175,927 ±8,796	0.176 ±0.012	0.068 ±0.005
Whitman Glacier	WHI	15	1,938,793 ±96,940	1.939 ±0.108	0.749 ±0.042
Wilson Glacier	WIL	17	1,562,401 ±78,120	1.562 ±0.088	0.603 ±0.034
Winthrop Glacier	WIN	2	8,976,552 ±448,828	8.977 ±0.474	3.466 ±0.183
Other Ice/Snow (total)	OTH	-	2,063,830 ±103,192	2.064 ±0.117	0.797 ±0.045
		Total (Excluding ice/snow):	**78,758,399 ±1,112,929**	**78.758 ±1.113**	**30.409 ±0.430**
		Total (All):	**80,822,229 ±1,119,073**	**80.822 ±1.119**	**31.206 ±0.432**

2015 Debris Cover

Nineteen of the 29 glaciers at Mount Rainier had conspicuous debris cover and were mapped (Figure 4). The Carbon Glacier had the most debris cover (Appendix A-2), owning to its source area below Willis Wall, which amounted to 4.84 ±0.27 km^2 (1.87 ±0.11 mi^2) (Figure 4). Most of the larger surface area glaciers had some debris on them and a majority of the terminal areas of these glaciers had complete debris cover. The Emmons Glacier exemplifies this – of its 2.98 ±0.17 km^2 (1.15 ±0.07

mi^2) debris cover, almost all was below 2,500 m (8,000 ft) (Appendix A-6). The Winthrop Glacier, the north neighbor to the Emmons, appeared to show glacial ogives in its debris cover between 1800-2500 m (6,000-8,000 ft) (Appendix A-30).

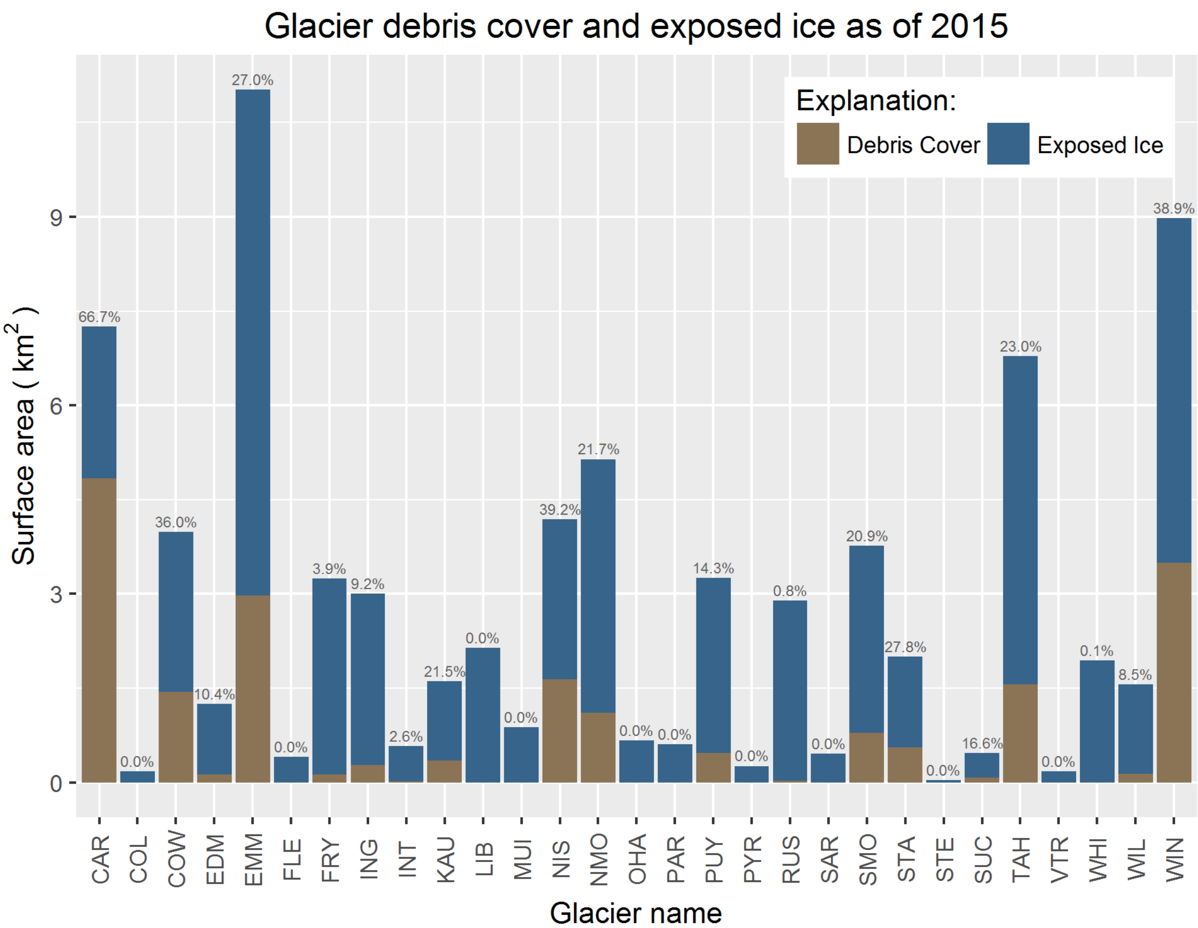

Figure 4. Extents of glacial debris cover and exposed ice on glaciers at Mount Rainier in 2015, based on data from Table 3. The value at the top of each column is the percentage of debris cover on each glacier. Glacier name identification can be found in Table 2.

The total area of debris cover in 2015 on Mount Rainier Glaciers was 20.01 ±0.42 km^2 (7.73 ±0.16 mi^2) (Table 3). This means that approximately 25.4% of the glacial area in 2015 was debris-covered ice.

Table 3. Extent of debris-covered area on glaciers in 2015 at Mount Rainier.

Glacier name	Rank[A]	m^2	km^2	mi^2	% Debris Cover[B]
Carbon Glacier	1	4,843,513 ±28,737	4.844 ±0.271	1.870 ±0.105	66.74
Columbia Crest Glacier	---	---	---	---	---
Cowlitz Glacier	6	1,437,542 ±15,656	1.438 ±0.088	0.555 ±0.034	36.03
Edmunds Glacier	14	130,169 ±4,711	0.130 ±0.011	0.050 ±0.004	10.39
Emmons Glacier	3	2,975,390 ±22,523	2.975 ±0.171	1.149 ±0.066	26.98
Flett Glaciers	---	---	---	---	---
Fryingpan Glacier	15	127,861 ±4,669	0.128 ±0.011	0.049 ±0.004	3.94
Ingraham Glacier	12	275,777 ±6,857	0.276 ±0.021	0.106 ±0.008	9.17
Inter Glacier	18	14,929 ±1,595	0.015 ±0.002	0.006 ±0.001	2.60
Kautz Glacier	11	346,109 ±7,682	0.346 ±0.025	0.134 ±0.010	21.48
Liberty Cap Glacier	---	---	---	---	---
Muir Snowfield	---	---	---	---	---
Nisqually Glacier	4	1,641,081 ±16,727	1.641 ±0.099	0.634 ±0.038	39.15
North Mowich Glacier	7	1,114,332 ±13,784	1.114 ±0.070	0.430 ±0.027	21.66
Ohanapecosh Glacier	---	---	---	---	---
Paradise Glacier	---	---	---	---	---
Puyallup Glacier	10	465,531 ±8,909	0.466 ±0.032	0.180 ±0.012	14.29
Pyramid Glacier	---	---	---	---	---
Russell Glacier	17	22,947 ±1,978	0.023 ±0.003	0.009 ±0.001	0.79
Sarvent Glaciers	---	---	---	---	---
South Mowich Glacier	8	788,009 ±11,591	0.788 ±0.051	0.304 ±0.020	20.93
South Tahoma Glacier	9	556,626 ±9,742	0.557 ±0.038	0.215 ±0.015	27.81
Stevens Glacier	---	---	---	---	---
Success Glacier	16	78,136 ±3,650	0.078 ±0.008	0.030 ±0.003	16.63
Tahoma Glacier	5	1,560,409 ±16,311	1.560 ±0.094	0.602 ±0.036	22.99
Van Trump Glaciers	---	---	---	---	---
Whitman Glacier	19	1,327 ±476	0.001 ±0.001	0.001 ±0.000	0.07
Wilson Glacier	13	132,747 ±7,757	0.133 ±0.011	0.051 ±0.004	8.50
Winthrop Glacier	2	3,493,999 ±24,407	3.494 ±0.199	1.349 ±0.077	38.92
	Total:	**20,006,434 ±424,357**	**20.006 ±0.424**	**7.725 ±0.164**	**25.40**[C]

[A] Features with no mapped debris cover are signified with a dash (e.g.: "---") for all columns and therefore are not counted in the overall rank.

[B] Percent debris cover is calculated as debris cover area (from this table) divided by total glacial area (from Table 2).

[C] Park-wide debris cover percentage is calculated as the total debris cover area (from this table) divided by the total glacier area (from Table 2), and does not account for other mapped snowfields or perennial snow. Factoring in these areas, the park-wide percent debris cover decreases to 24.75%.

Extent comparison over time

In order to better understand the temporal changes to glacial area at Mount Rainier, the 2015 inventory was compared to glacial inventories which were completed in 1896, 1913, 1971, 1994, and 2009. Figure 5 and Table 4 show the comparison of the 2015 inventory with the previous five inventories. Table 5 shows the total area change in extent between inventories and Table 6 shows the total percentage change in extent between inventories.

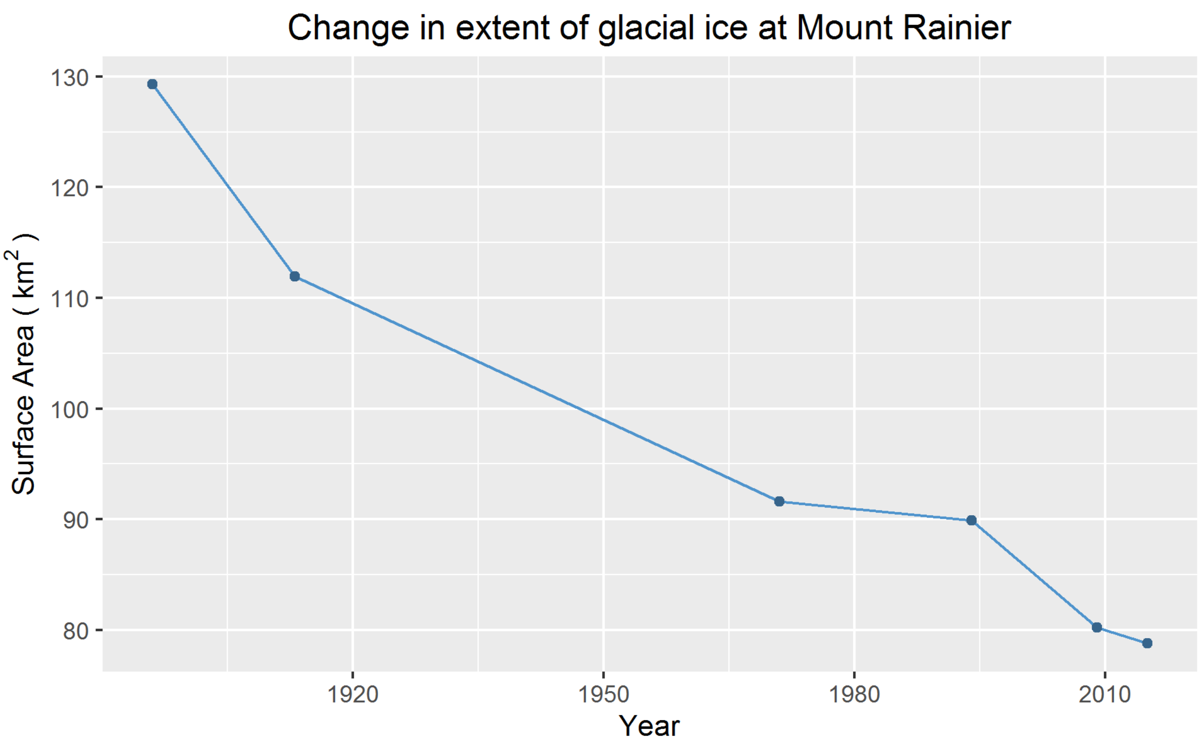

Figure 5. Overall change in surface area for all glaciers at Mount Rainier from 1896-2015, based on data in Table 4.

Table 4. Comparison of extents of glaciers at Mount Rainier over time (excluding unnamed perennial ice/snow fields). Values listed are in square kilometers (km^2). The Flett, Ohanapecosh and Sarvent Glaciers were not mapped in 1896.

Glacier Name	1896	1913	1971	1994	2009	2015
Carbon Glacier	8.29	8.46	8.01	7.98	7.45	7.26
Columbia Crest Glacier	0.32	0.11	0.25	0.20	0.12	0.18
Cowlitz-Ingraham Glaciers	8.31	9.84	7.64	7.70	7.05	7.00
Edmunds Glacier	2.82	1.53	1.47	1.42	1.30	1.25
Emmons Glacier	17.46	12.62	11.16	11.22	10.98	11.03
Flett Glacier	---	0.74	0.58	0.62	0.58	0.41
Fryingpan Glacier	3.72	6.12	4.34	4.23	3.30	3.24
Inter Glacier	0.57	1.14	0.84	0.83	0.67	0.57
Kautz-Success Glaciers	5.17	3.03	2.73	2.20	2.13	2.08
Liberty Cap Glacier	2.82	2.40	2.08	2.10	2.20	2.14
Muir Snowfield	1.13	1.22	0.97	0.98	0.92	0.88
Nisqually-Wilson Glaciers	10.03	6.59	6.07	6.25	6.00	5.75
North Mowich Glacier	11.07	8.03	6.26	6.11	5.21	5.14
Ohanapecosh Glacier	---	2.97	1.37	1.39	0.79	0.67
Paradise-Stevens Glaciers	4.86	3.19	1.36	1.34	0.78	0.64
Puyallup Glacier	8.46	5.21	4.32	4.35	3.52	3.26
Pyramid Glacier	2.75	1.39	0.71	0.64	0.38	0.26
Russell Glacier	6.61	4.91	3.57	3.64	2.79	2.89
Sarvent Glaciers	---	1.15	0.69	0.15	0.69	0.45
South Mowich Glacier	5.33	4.70	4.09	4.06	3.96	3.77
South Tahoma Glacier	5.93	3.43	2.92	2.23	2.21	2.00
Tahoma Glacier	12.00	9.17	7.62	7.28	6.78	6.79
Van Trump Glaciers	1.44	1.40	0.68	0.72	0.32	0.18
Whitman Glacier	1.97	2.43	2.23	2.32	2.10	1.94
Winthrop Glacier	8.23	10.18	9.63	9.94	8.01	8.98
Total	**129.31**	**111.95**	**91.58**	**89.88**	**80.22**	**78.76**

Table 5. Total area change in extent between inventory periods for each glacier at Mount Rainier. Listed units are in square kilometers (km^2). Average change is the total change in each period divided by the years between by those periods; units are in average square kilometers per year ($km^2 \times yr^{-1}$). (km^2 unit sign omitted for clarity).

Glacier Name	1896-1913	1896-1971	1896-1994	1896-2009	1896-2015	1913-1971	1913-1994	1913-2009	1913-2015	1971-1994	1971-2009	1971-2015	1994-2009	1994-2015	2009-2015
Carbon	0.17	-0.28	-0.31	-0.84	-1.03	-0.44	-0.48	-1.00	-1.20	-0.04	-0.56	-0.76	-0.52	-0.72	-0.20
Columbia Crest	-0.21	-0.07	-0.12	-0.20	-0.14	0.14	0.09	0.01	0.07	-0.05	-0.13	-0.07	-0.08	-0.02	0.06
Cowlitz-Ingraham	1.53	-0.67	-0.61	-1.26	-1.31	-2.20	-2.14	-2.79	-2.84	0.06	-0.59	-0.64	-0.65	-0.70	-0.05
Edmunds	-1.29	-1.35	-1.40	-1.52	-1.57	-0.06	-0.11	-0.23	-0.28	-0.06	-0.17	-0.22	-0.12	-0.16	-0.05
Emmons	-4.84	-6.30	-6.24	-6.48	-6.43	-1.46	-1.40	-1.64	-1.60	0.06	-0.18	-0.13	-0.24	-0.20	0.05
Flett	---	---	---	---	---	-0.16	-0.12	-0.15	-0.33	0.04	0.01	-0.17	-0.03	-0.21	-0.18
Fryingpan	2.40	0.62	0.51	-0.43	-0.48	-1.78	-1.89	-2.82	-2.88	-0.11	-1.04	-1.09	-0.93	-0.99	-0.05
Inter	0.57	0.27	0.26	0.10	0.00	-0.31	-0.32	-0.48	-0.57	-0.01	-0.17	-0.26	-0.16	-0.25	-0.09
Kautz-Success	-2.15	-2.45	-2.97	-3.05	-3.09	-0.30	-0.83	-0.90	-0.95	-0.53	-0.60	-0.65	-0.08	-0.12	-0.04
Liberty Cap	-0.42	-0.74	-0.72	-0.62	-0.68	-0.32	-0.30	-0.20	-0.26	0.02	0.12	0.06	0.10	0.04	-0.06
Muir Snowfield	0.08	-0.16	-0.16	-0.21	-0.26	-0.25	-0.24	-0.30	-0.34	0.01	-0.05	-0.09	-0.06	-0.10	-0.04
Nisqually-Wilson	-3.44	-3.95	-3.77	-4.02	-4.27	-0.52	-0.33	-0.59	-0.83	0.18	-0.07	-0.32	-0.25	-0.50	-0.25
North Mowich	-3.04	-4.81	-4.97	-5.87	-5.93	-1.77	-1.92	-2.83	-2.89	-0.15	-1.05	-1.12	-0.90	-0.96	-0.06
Ohanapecosh	---	---	---	---	---	-1.60	-1.58	-2.18	-2.30	0.02	-0.58	-0.70	-0.60	-0.72	-0.12
Paradise-Stevens	-1.68	-3.50	-3.53	-4.09	-4.22	-1.82	-1.85	-2.41	-2.54	-0.03	-0.59	-0.72	-0.56	-0.69	-0.13
Puyallup	-3.25	-4.15	-4.12	-4.94	-5.21	-0.90	-0.86	-1.69	-1.95	0.03	-0.80	-1.06	-0.83	-1.09	-0.26
Pyramid	-1.35	-2.04	-2.10	-2.37	-2.48	-0.68	-0.75	-1.02	-1.13	-0.06	-0.33	-0.45	-0.27	-0.38	-0.12
Russell	-1.70	-3.03	-2.97	-3.82	-3.71	-1.33	-1.27	-2.12	-2.02	0.06	-0.78	-0.68	-0.85	-0.74	0.10
Sarvent	---	---	---	---	---	-0.46	-1.00	-0.45	-0.69	-0.54	0.01	-0.23	0.55	0.31	-0.24
South Mowich	-0.63	-1.24	-1.27	-1.37	-1.57	-0.61	-0.64	-0.74	-0.93	-0.03	-0.13	-0.33	-0.10	-0.30	-0.20
South Tahoma	-2.50	-3.00	-3.69	-3.72	-3.92	-0.51	-1.19	-1.22	-1.43	-0.69	-0.72	-0.92	-0.03	-0.23	-0.20
Tahoma	-2.83	-4.39	-4.72	-5.23	-5.22	-1.55	-1.89	-2.39	-2.38	-0.34	-0.84	-0.83	-0.50	-0.49	0.01

Table 5 (continued). Total area change in extent between inventory periods for each glacier at Mount Rainier. Listed units are in square kilometers (km^2). Average change is the total change in each period divided by the years between by those periods; units are in average square kilometers per year ($km^2 \times yr^{-1}$). (km^2 unit sign omitted for clarity).

Glacier Name	1896-1913	1896-1971	1896-1994	1896-2009	1896-2015	1913-1971	1913-1994	1913-2009	1913-2015	1971-1994	1971-2009	1971-2015	1994-2009	1994-2015	2009-2015
Van Trump	-0.04	-0.76	-0.71	-1.12	-1.26	-0.72	-0.68	-1.08	-1.23	0.04	-0.36	-0.51	-0.41	-0.55	-0.14
Whitman	0.46	0.25	0.34	0.13	-0.04	-0.21	-0.12	-0.33	-0.49	0.09	-0.12	-0.29	-0.21	-0.38	-0.16
Winthrop	1.95	1.40	1.71	-0.22	0.74	-0.55	-0.24	-2.17	-1.21	0.31	-1.62	-0.65	-1.93	-0.97	0.96
Total Change	**-22.21**	**-40.36**	**-41.58**	**-51.15**	**-52.08**	**-20.37**	**-22.07**	**-31.73**	**-33.19**	**-1.70**	**-11.36**	**-12.82**	**-9.66**	**-11.12**	**-1.46**
Years	**17**	**75**	**98**	**113**	**119**	**58**	**81**	**96**	**102**	**23**	**38**	**44**	**15**	**21**	**6**
Average Change	**-1.31**	**-0.54**	**-0.42**	**-0.45**	**-0.44**	**-0.35**	**-0.27**	**-0.33**	**-0.33**	**-0.07**	**-0.30**	**-0.29**	**-0.64**	**-0.53**	**-0.24**

Table 6. Total percent change in extent between inventory periods for each glacier at Mount Rainier. Listed units are percent (%). Average change is the total change in each period divided by the years between by those periods; units are average percent per year ($\% \times yr^{-1}$). (% sign omitted for clarity).

Glacier Name	1896-1913	1896-1971	1896-1994	1896-2009	1896-2015	1913-1971	1913-1994	1913-2009	1913-2015	1971-1994	1971-2009	1971-2015	1994-2009	1994-2015	2009-2015
Carbon	2.0	-3.3	-3.8	-10.1	-12.5	-5.2	-5.7	-11.8	-14.2	-0.5	-7.0	-9.4	-6.5	-9.0	-2.7
Columbia Crest	-66.8	-22.1	-38.6	-63.4	-43.9	134.6	84.9	10.4	68.8	-21.2	-53.0	-28.0	-40.3	-8.7	53.0
Cowlitz-Ingraham	18.4	-8.1	-7.4	-15.2	-15.8	-22.3	-21.8	-28.4	-28.9	0.8	-7.7	-8.4	-8.4	-9.1	-0.7
Edmunds	-45.7	-47.7	-49.8	-53.9	-55.6	-3.7	-7.4	-15.0	-18.1	-3.9	-11.8	-15.0	-8.2	-11.6	-3.7
Emmons	-27.7	-36.1	-35.7	-37.1	-36.8	-11.6	-11.1	-13.0	-12.6	0.6	-1.6	-1.2	-2.2	-1.7	0.4
Flett	---	---	---	---	---	-21.7	-16.5	-21.0	-44.9	6.8	1.0	-29.6	-5.4	-34.1	-30.3
Fryingpan	64.5	16.6	13.7	-11.4	-12.8	-29.1	-30.9	-46.1	-47.0	-2.5	-24.0	-25.2	-22.1	-23.3	-1.6
Inter	100.5	46.6	44.8	16.7	0.7	-26.9	-27.8	-41.8	-49.8	-1.2	-20.4	-31.3	-19.4	-30.5	-13.7

Table 6 (continued). Total percent change in extent between inventory periods for each glacier at Mount Rainier. Listed units are percent (%). Average change is the total change in each period divided by the years between by those periods; units are average percent per year (% × yr^{-1}). (% sign omitted for clarity).

Glacier Name	1896-1913	1896-1971	1896-1994	1896-2009	1896-2015	1913-1971	1913-1994	1913-2009	1913-2015	1971-1994	1971-2009	1971-2015	1994-2009	1994-2015	2009-2015
Kautz-Success	-41.5	-47.3	-57.5	-58.9	-59.8	-9.9	-27.3	-29.8	-31.3	-19.3	-22.1	-23.7	-3.4	-5.5	-2.1
Liberty Cap	-14.9	-26.3	-25.5	-22.1	-24.2	-13.4	-12.4	-8.4	-10.9	1.1	5.8	2.9	4.7	1.8	-2.8
Muir Snowfield	7.4	-14.5	-13.7	-18.7	-22.7	-20.4	-19.7	-24.3	-28.0	0.9	-5.0	-9.6	-5.8	-10.4	-4.9
Nisqually-Wilson	-34.3	-39.4	-37.6	-40.1	-42.6	-7.8	-5.1	-8.9	-12.7	3.0	-1.1	-5.2	-4.0	-8.0	-4.2
North Mowich	-27.5	-43.5	-44.8	-53.0	-53.5	-22.1	-24.0	-35.2	-36.0	-2.4	-16.8	-17.8	-14.8	-15.8	-1.2
Ohanapecosh	---	---	---	---	---	-53.9	-53.2	-73.5	-77.5	1.4	-42.6	-51.2	-43.4	-51.8	-14.8
Paradise-Stevens	-34.5	-72.0	-72.5	-84.0	-86.7	-57.2	-58.0	-75.6	-79.8	-1.9	-43.0	-52.7	-41.9	-51.8	-17.1
Puyallup	-38.4	-49.0	-48.6	-58.4	-61.5	-17.2	-16.6	-32.5	-37.5	0.7	-18.5	-24.5	-19.1	-25.1	-7.4
Pyramid	-49.2	-74.2	-76.5	-86.2	-90.5	-49.1	-53.7	-72.8	-81.2	-9.1	-46.6	-63.0	-41.3	-59.3	-30.7
Russell	-25.7	-45.9	-44.9	-57.8	-56.2	-27.2	-25.9	-43.2	-41.1	1.8	-22.0	-19.1	-23.3	-20.5	3.7
Sarvent	---	---	---	---	---	-40.2	-87.3	-39.4	-60.4	-78.8	1.3	-33.7	377.0	212.1	-34.6
South Mowich	-11.8	-23.3	-23.8	-25.7	-29.2	-13.0	-13.6	-15.7	-19.9	-0.7	-3.1	-8.0	-2.4	-7.3	-5.0
South Tahoma	-42.2	-50.7	-62.3	-62.8	-66.2	-14.8	-34.9	-35.6	-41.6	-23.6	-24.5	-31.5	-1.2	-10.3	-9.3
Tahoma	-23.6	-36.5	-39.4	-43.5	-43.5	-16.9	-20.6	-26.1	-26.0	-4.4	-11.1	-10.9	-6.9	-6.8	0.2
Van Trump	-2.5	-52.6	-49.6	-77.9	-87.8	-51.4	-48.3	-77.3	-87.5	6.3	-53.4	-74.2	-56.2	-75.7	-44.6
Whitman	23.2	12.7	17.3	6.4	-1.8	-8.5	-4.8	-13.6	-20.3	4.0	-5.6	-12.9	-9.2	-16.3	-7.7
Winthrop	23.7	17.0	20.8	-2.7	9.0	-5.4	-2.4	-21.3	-11.8	3.2	-16.8	-6.8	-19.4	-9.7	12.0
Total Change	**-13.4**	**-29.2**	**-30.5**	**-38.0**	**-39.1**	**-18.2**	**-19.7**	**-28.3**	**-29.6**	**-1.9**	**-12.4**	**-14.0**	**-10.7**	**-12.4**	**-1.8**
Years	**17**	**75**	**98**	**113**	**119**	**58**	**81**	**96**	**102**	**23**	**38**	**44**	**15**	**21**	**6**
Average Change	**-0.79**	**-0.39**	**-0.31**	**-0.34**	**-0.33**	**-0.31**	**-0.24**	**-0.30**	**-0.29**	**-0.08**	**-0.33**	**-0.32**	**-0.72**	**-0.59**	**-0.30**

Figure 6 shows the changes in glacial area for those glaciers and glacial systems (e.g., Nisqually and Wilson Glaciers together) whose 2015 surface area is greater than 5 km^2 (1.9 mi^2). Figure 7 shows glaciers and glacial systems whose area is between 1 – 5 km^2 (0.4 – 1.9 mi^2) and Figure 8 shows glaciers and glacial systems whose area is less than 1 km^2 (0.4 mi^2). Maps showing changes to all glaciers and glacial systems between 1896 and 2015 are included in Appendix B. A smaller scale map showing the entire park is attached as Plate 2. It should be noted that while there was an overall decrease in glacial area between 1970 and 1995, some glaciers in Figures 6-8 showed area growth during the same period. This is likely due to individual variation in glaciers. Additionally, Hodge (1974) found that there is approximately a 15-year lag time between accumulation of glacial ice and noted advance at the terminal regions of glaciers.

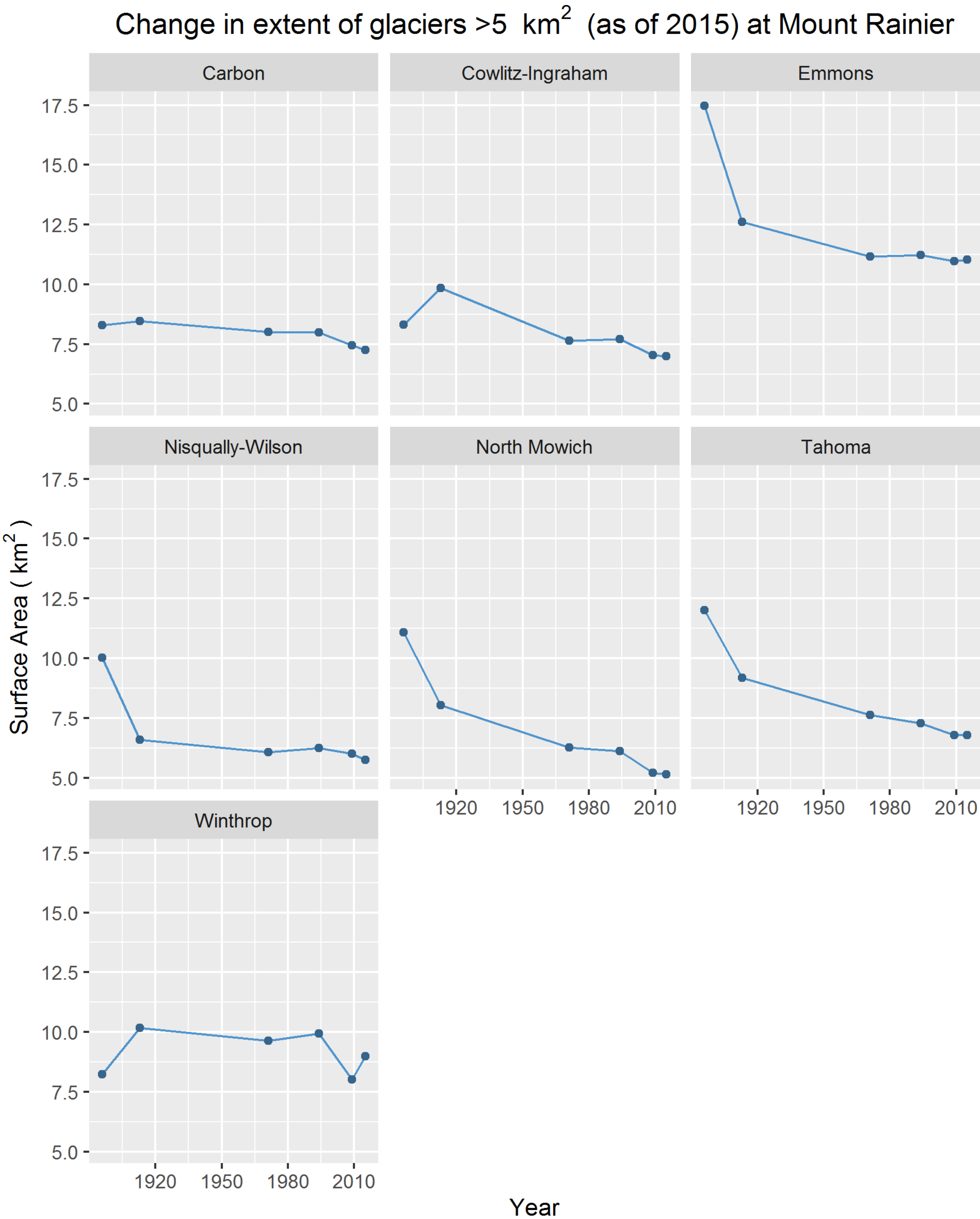

Figure 6. Change in surface area of glaciers from 1896 to 2015 that had a 2015 extent greater than five square kilometers, based on data in Table 4.

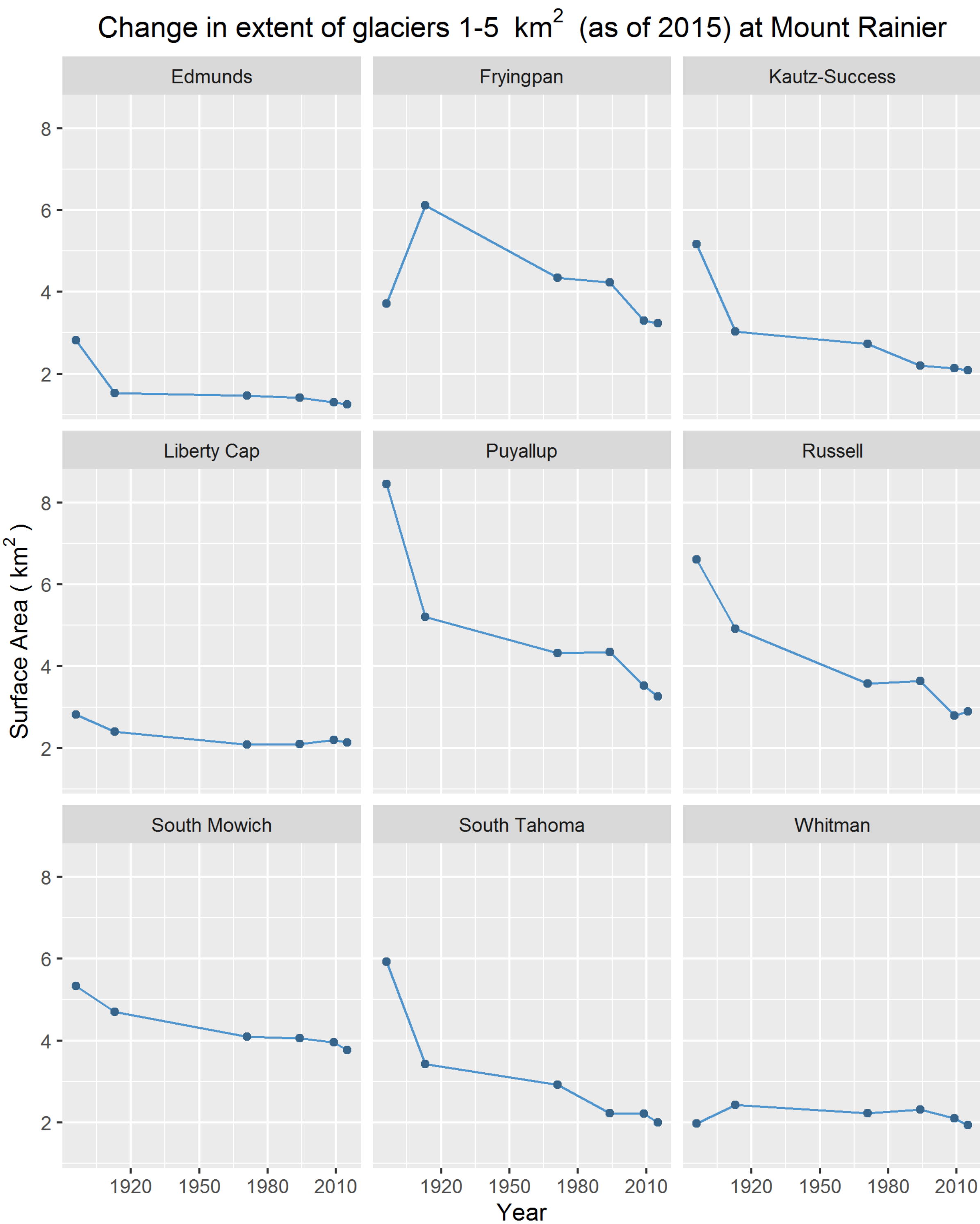

Figure 7. Change in surface area of glaciers from 1896 to 2015 that had a 2015 extent between 1 and 5 square kilometers, based on data in Table 4.

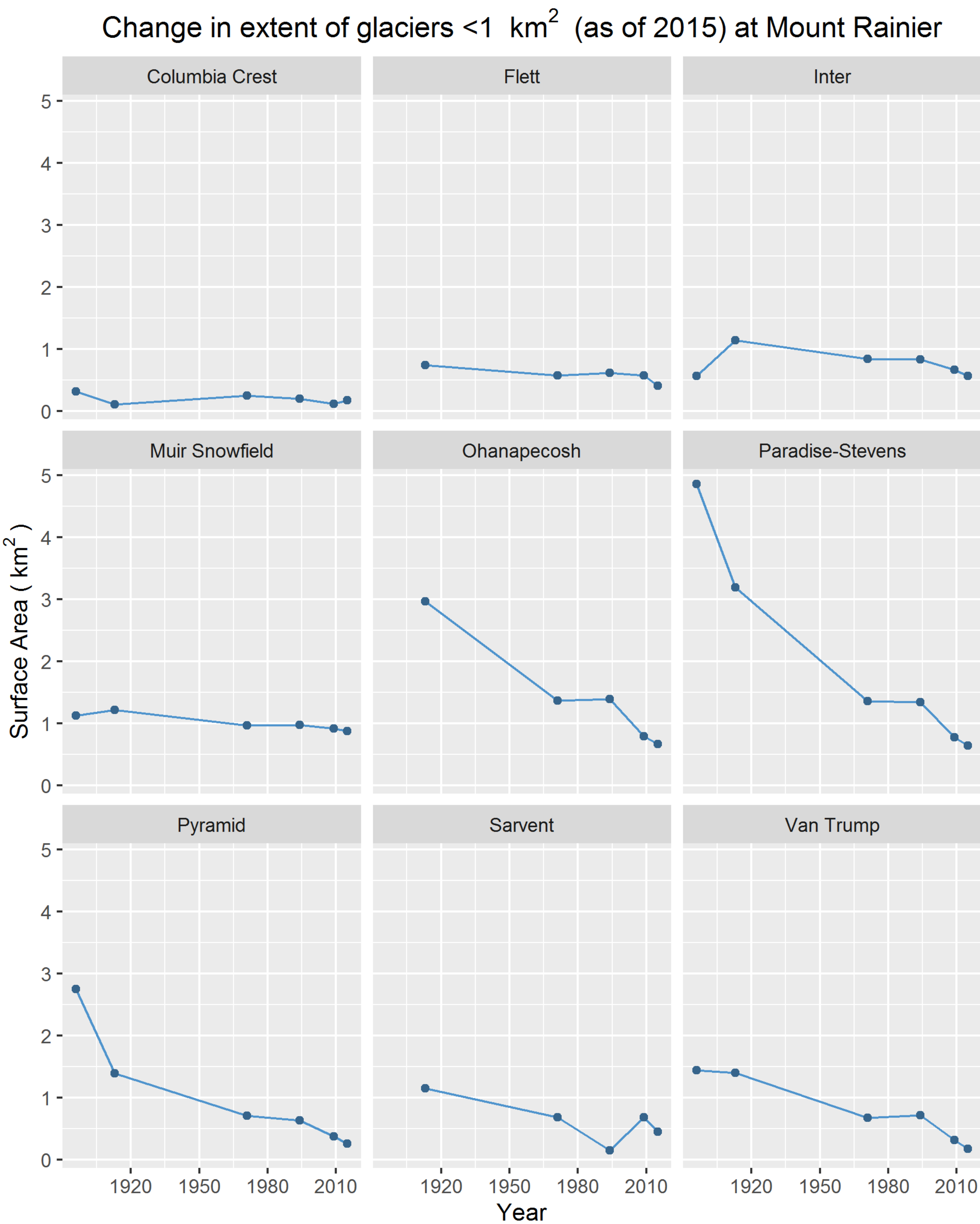

Figure 8. Change in surface area of glaciers from 1896 to 2015 that had a 2015 extent less than 1 square kilometer, based on data in Table 4.

The total loss of glacial area between 1896 and 2015 was 50.55 km^2 (19.52 mi^2) (Figure 5, Table 4). All time periods showed loss of glacial area; however, the period between 1896 and 1913 had the fastest rate of surface area decrease (1.02 $km^2 \times yr^{-1}$ [0.39 $mi^2 \times yr^{-1}$]) (Figure 5). The period between 2009 and 2015 had the second fastest rate of surface area decrease (0.64 $km^2 \times yr^{-1}$ [0.25 $mi^2 \times yr^{-1}$]). The period between 1971 and 1994 had the slowest area loss rate of 0.07 $km^2 \times yr^{-1}$ (0.03 $mi^2 \times yr^{-1}$). Many glaciers in the park, including the Carbon, Cowlitz, Emmons and Nisqually advanced during the late 1970s and early 1980s due to high snow fall totals that occurred in the 1960s and 1970s (Driedger, 1993), and rock falls that occurred on the Emmons Glacier (Crandell and Fahnestock 1965).

Changes in Extent by Aspect

Figure 9 and Table 7 show the change in surface area of glaciers by aspect at Mount Rainier. For the purposes of this study, the northern aspect glaciers include the Carbon, Edmunds, Emmons, Flett, Fryingpan, Inter, Liberty Cap, North Mowich, Russell, Sarvent, and Winthrop Glaciers; while the south aspect glaciers include the Columbia Crest, Cowlitz, Ingraham, Kautz, Muir Snowfield, Nisqually, Ohanapecosh, Paradise, Puyallup, Pyramid, South Mowich, South Tahoma, Stevens, Success, Tahoma, Van Trump, Whitman, and Wilson Glaciers.

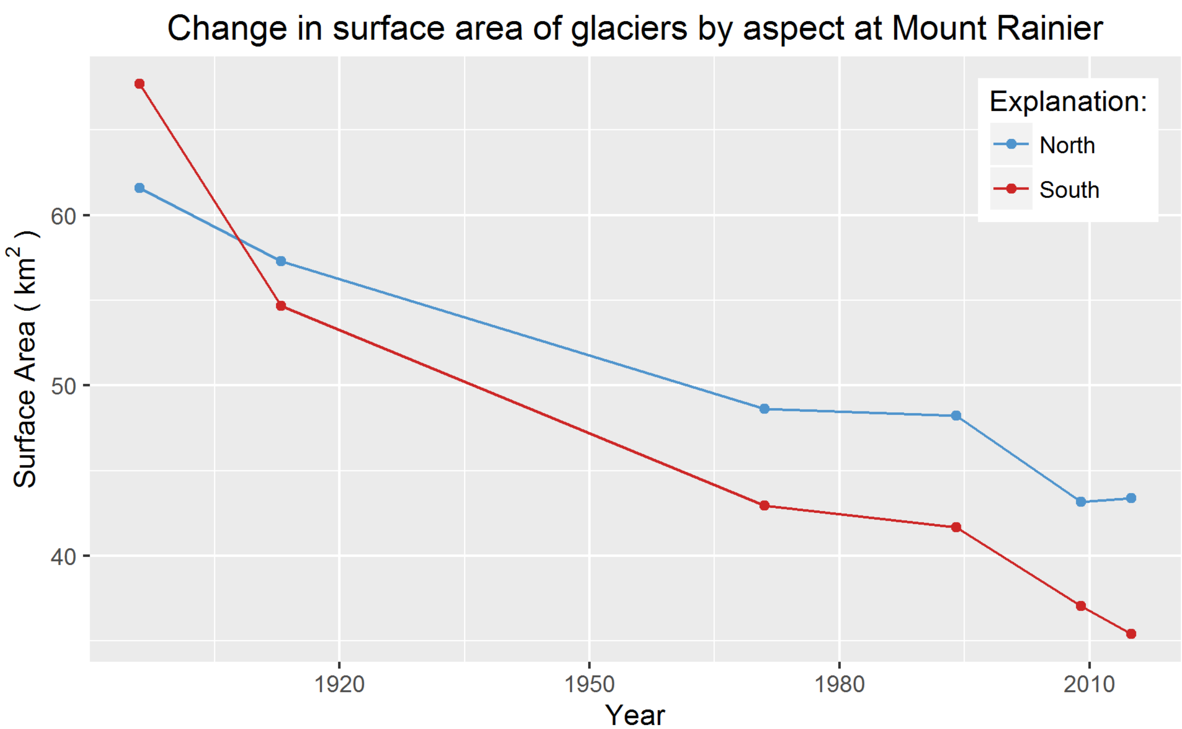

Figure 9. Change in extent of glaciers by aspect from 1896 to 2015 at Mount Rainier, based on data from Table 7.

Table 7. Changes in surface area of glaciers by aspect at Mount Rainier for various time periods. Listed units are in square kilometers (km^2)

Aspect	1896	1913	1971	1994	2009	2015	1896-2015 Change (km2)	1896-2015 Change (%)
North[1]	61.60	57.28	48.63	48.22	43.18	43.31	-18.28	-29.7%
South[1]	67.71	54.67	42.95	41.66	37.07	35.35	-32.36	-47.8%

[1] See text for the listing of which glaciers fall into the north and south aspects of Mount Rainier.

South facing glaciers, which are exposed to more solar radiation throughout the year, have seen a more rapid loss of surface area of 32.36 km^2 (12.49 mi^2) compared to 18.28 km^2 (7.06 mi^2). This corresponds to an average annual loss of 0.27 km^2 per year (0.10 $mi^2 \times yr^{-1}$) for the south and 0.15 km^2 per year (0.06 $mi^2 \times yr^{-1}$) for the north aspect glaciers. Other factors that may account for volume changes by aspect include secondary snow accumulation by avalanches and wind drifting, especially on the northeast aspect of the mountain.

Glacier Statistics

Table 8 shows statistics calculated on each glacier based on the mapped extents in 2015 and the latest park-wide LiDAR topography, which was acquired in 2007/2008.

The Columbia Crest Glacier had a unique situation in which the glacier occupies the space within the east and west crater rims on Mount Rainier. This situation does not allow for the glacier to flow any direction and thus, some of the statistics of the glacier may appear to be unreasonable based on comparison with other glaciers. Some glaciers had multiple mapped features. In these cases, the elevation maximum, minimum, and ranges were calculated on all mapped features rather than the largest mapped feature. Average slope and flow direction in these situations were averaged over all of the features.

Table 8. Statistics of glaciers at Mount Rainier based on 2015 delineation.

	Max Elevation		Min Elevation		Elevation Range		Length		Avg. Slope	Avg. Flow Dir	
Glacier	**m**	**ft**	**m**	**ft**	**m**	**ft**	**km**	**mi**	**°**	**°**	**Card. Dir**
Carbon Glacier	3,745	12,288	1,082	3,550	2,663	8,738	8.39	5.22	25.05	344	NNW
Columbia Crest Glacier	4,393	14,411	4,311	14,145	81	267	0.68	0.43	10.78	112	ESE
Cowlitz Glacier	3,405	11,171	1,610	5,281	1,795	5,890	5.83	3.62	24.99	121	ESE
Edmunds Glacier	3,088	10,130	2,127	6,979	960	3,151	2.12	1.32	25.29	280	W
Emmons Glacier	4,320	14,173	1,491	4,892	2,829	9,282	7.67	4.77	29.41	48	NE
Flett Glaciers	2,431	7,976	2,115	6,940	316	1,036	0.73	0.46	20.61	352	N
Fryingpan Glacier	3,030	9,940	2,183	7,161	847	2,779	1.97	1.23	24.09	34	NE
Ingraham Glacier	4,292	14,080	1,986	6,516	2,305	7,564	5.18	3.22	31.63	123	ESE
Inter Glacier	2,934	9,627	2,235	7,331	700	2,296	1.48	0.92	25.57	15	NNE
Kautz Glacier	4,313	14,150	2,070	6,792	2,243	7,358	4.25	2.64	35.54	199	SSW
Liberty Cap Glacier	4,304	14,121	3,226	10,585	1,078	3,537	2.71	1.69	29.69	314	NW
Muir Snowfield	3,076	10,092	2,482	8,142	595	1,950	1.91	1.19	18.14	184	S
Nisqually Glacier	4,388	14,397	1,615	5,297	2,773	9,099	6.18	3.84	30.40	174	S
North Mowich Glacier	3,717	12,195	1,634	5,360	2,083	6,835	4.47	2.78	27.81	316	NW
Ohanapecosh Glacier	2,599	8,526	2,156	7,075	442	1,451	0.86	0.54	21.75	73	ENE
Paradise Glacier	2,585	8,479	2,100	6,891	484	1,589	0.75	0.46	22.84	129	SE
Puyallup Glacier	3,122	10,244	1,687	5,534	1,435	4,709	4.29	2.66	21.22	279	W
Pyramid Glacier	2,965	9,728	2,272	7,455	693	2,273	1.23	0.77	20.87	188	S
Russell Glacier	2,978	9,772	2,043	6,704	935	3,068	2.80	1.74	23.14	18	NNE
Sarvent Glaciers	2,194	7,199	1,858	6,094	337	1,105	0.76	0.47	25.14	6	N
South Mowich Glacier	3,925	12,877	1,531	5,024	2,394	7,853	6.14	3.81	32.61	272	W
South Tahoma Glacier	3,299	10,823	2,037	6,684	1,262	4,139	3.29	2.05	28.47	226	SW
Stevens Glacier	2,085	6,840	1,989	6,527	95	313	0.57	0.36	19.72	113	ESE
Success Glacier	3,224	10,576	2,570	8,432	653	2,144	1.19	0.74	31.10	192	SSW
Tahoma Glacier	4,373	14,349	1,876	6,155	2,497	8,193	7.03	4.37	29.88	250	WSW

Table 8 (continued). Statistics of glaciers at Mount Rainier based on 2015 delineation.

	Max Elevation		Min Elevation		Elevation Range		Length		Avg. Slope	Avg. Flow Dir	
Glacier	**m**	**ft**	**m**	**ft**	**m**	**ft**	**km**	**mi**	**°**	**°**	**Card. Dir**
Van Trump Glaciers	2,815	9,236	2,201	7,221	614	2,015	1.42	0.88	25.89	176	S
Whitman Glacier	3,139	10,298	2,311	7,580	828	2,717	3.25	2.02	17.49	148	SSE
Wilson Glacier	3,303	10,838	2,032	6,667	1,271	4,170	2.11	1.31	29.89	148	SSE
Winthrop Glacier	4,383	14,379	1,475	4,840	2,907	9,539	8.03	4.99	28.78	13	NNE
Minimum:	**2,085**	**6,840**	**1,082**	**3,550**	**81**	**267**	**0.57**	**0.36**	**10.78**	---	---
Average:	**3,394**	**11,135**	**2,080**	**6,823**	**1,314**	**4,312**	**3.36**	**2.09**	**25.44**	---	---
Maximum:	**4,393**	**14,411**	**4,311**	**14,145**	**2,907**	**9,539**	**8.39**	**5.22**	**35.54**	---	---

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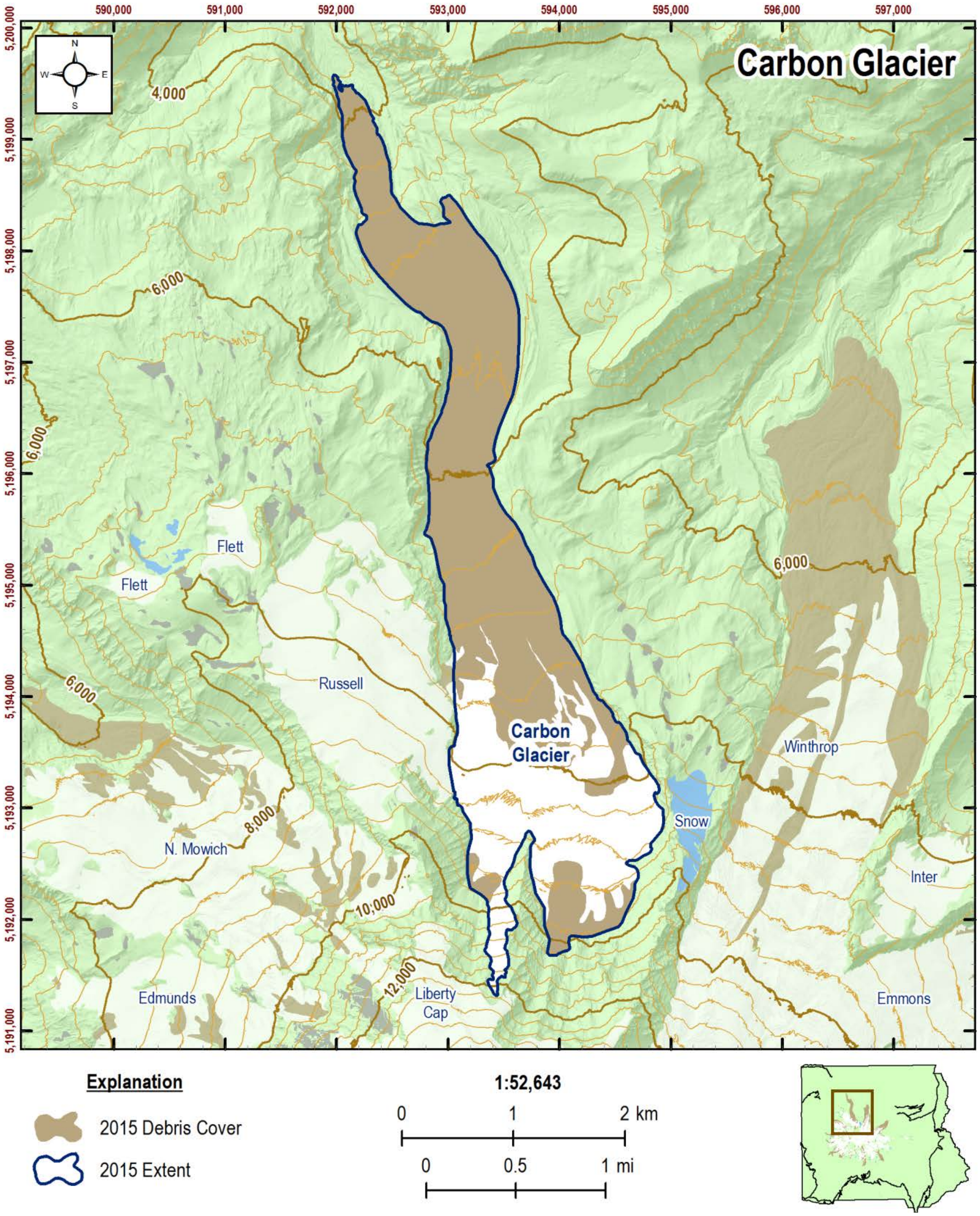
Appendix A: Detail maps of individual named glaciers at Mount Rainier.

Notes for all maps:

- Map grids are plotted in NAD 1983 UTM Zone 10 North (meters)
- Contours: 400 ft., 2000 ft. index contour, based on 2007/8 LiDAR Survey
- Background hill shade based on 2007/8 LiDAR Survey
- Rank and aerial extent of glaciers are from Table 1.
- Percentage of debris cover and rank are from Table 2.

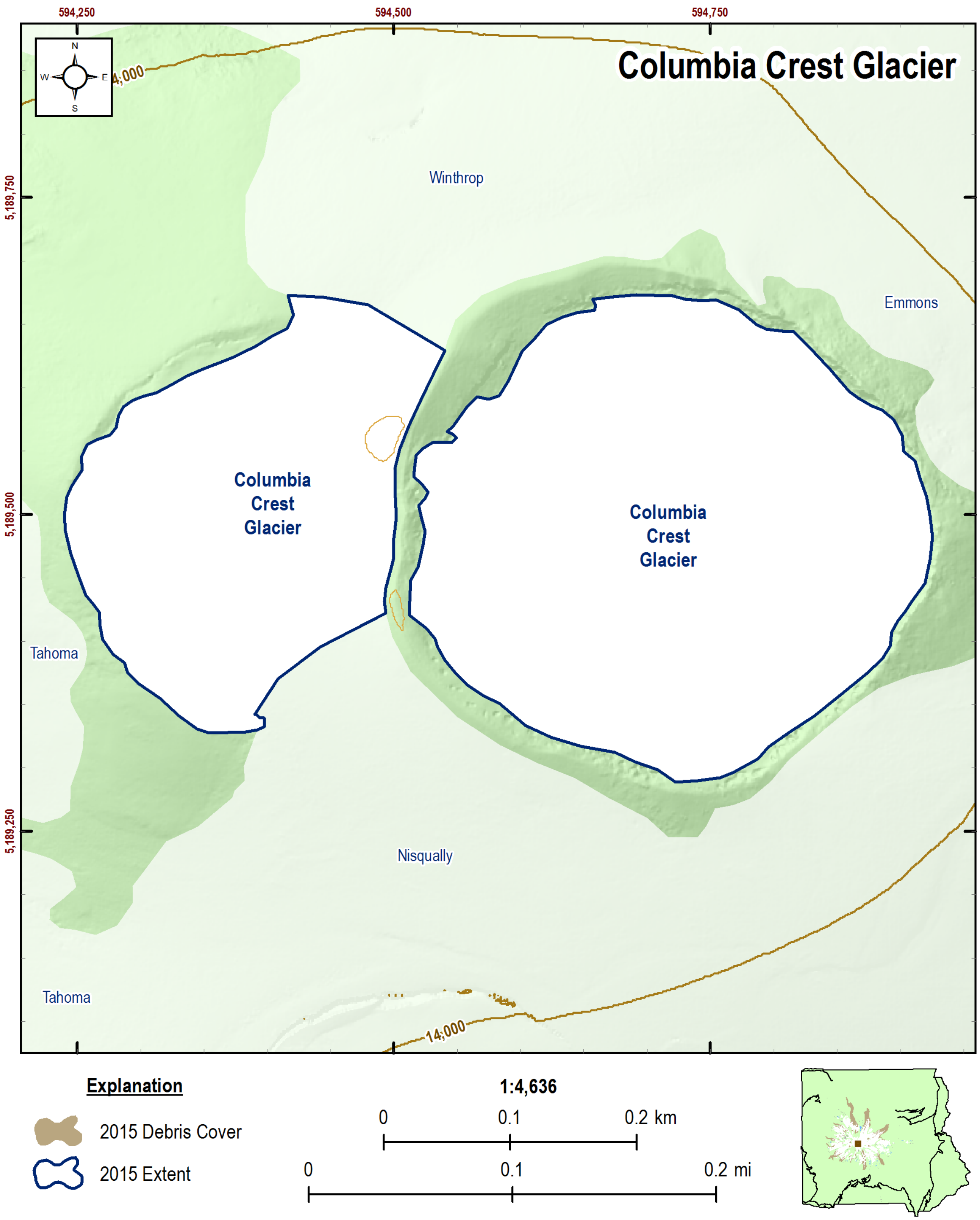
A large format map (ANSI-E; 34x44 in) encompassing the full park area is available separately (https://irma.nps.gov/DataStore/Reference/Profile/2242142) as Plate 1.

Appendix A-2: Carbon Glacier



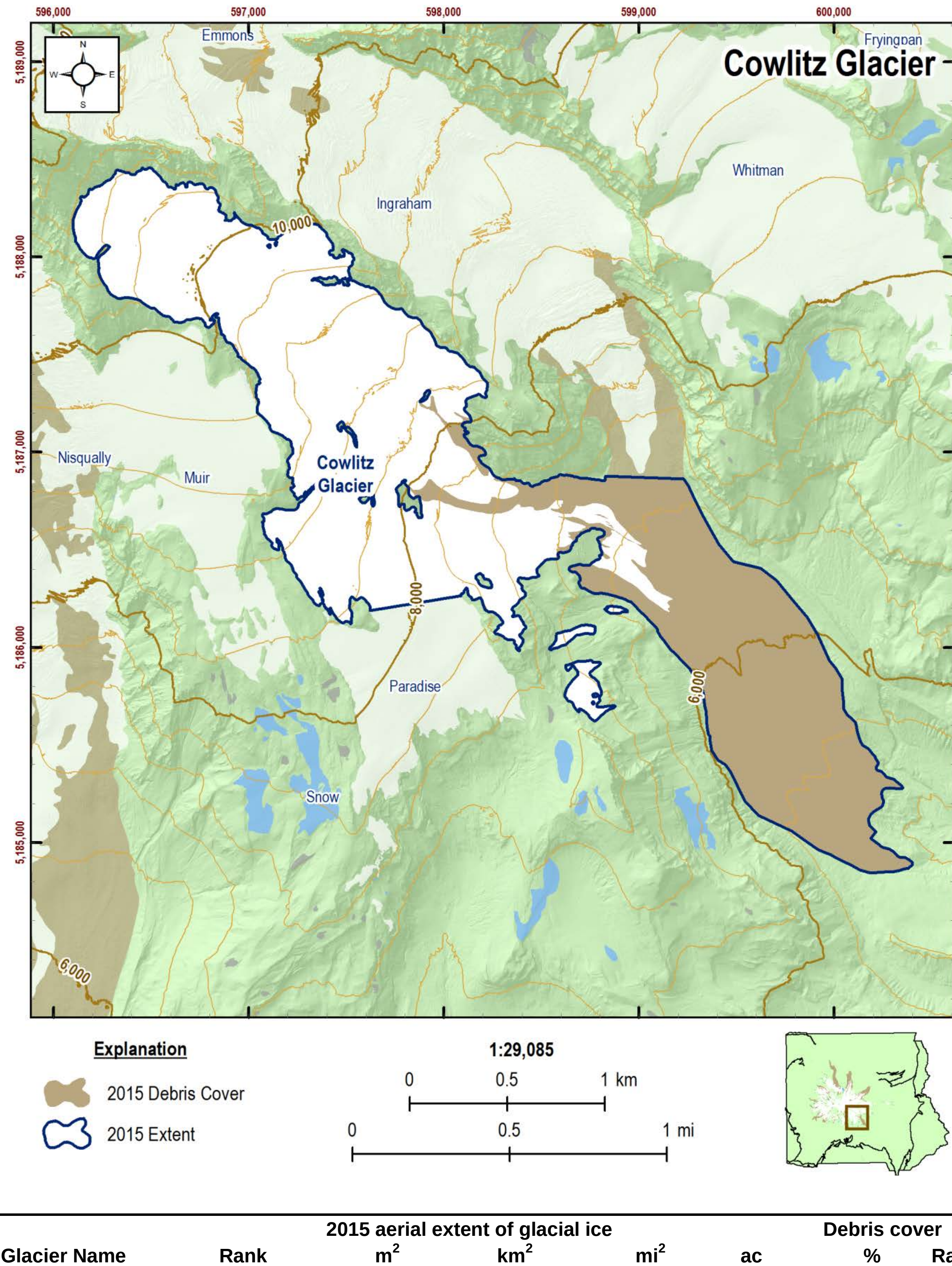
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Carbon Glacier	3	7,256,844	7.257	2.802	1,793	66.74	1

Appendix A-3: Columbia Crest Glacier



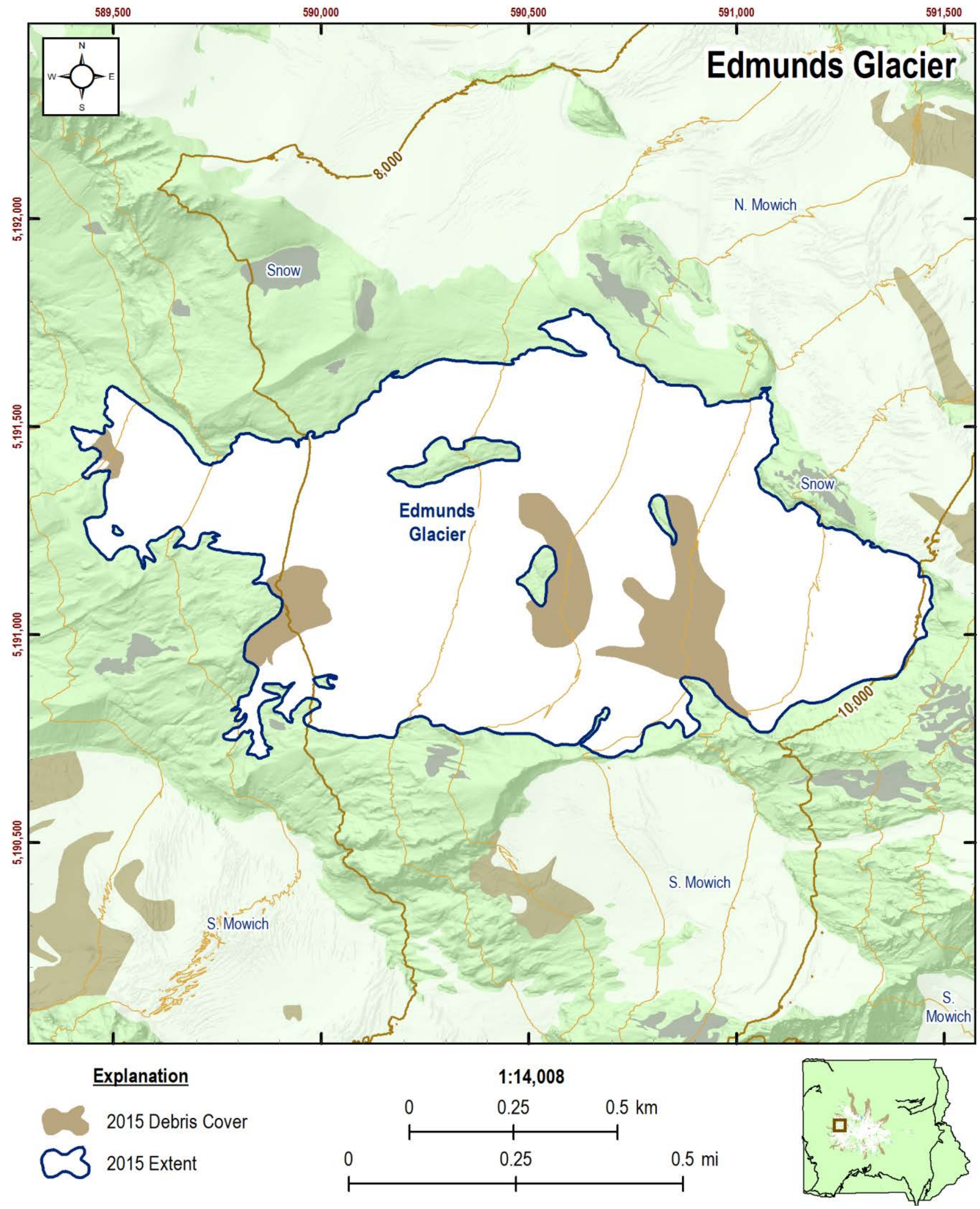
Glacier Name	Rank	2015 aerial extent of glacial ice m^2	km^2	mi^2	ac	Debris cover %	Rank
Columbia Crest Glacier	27	180,346	0.180	0.070	45	0	-

Appendix A-4: Cowlitz Glacier



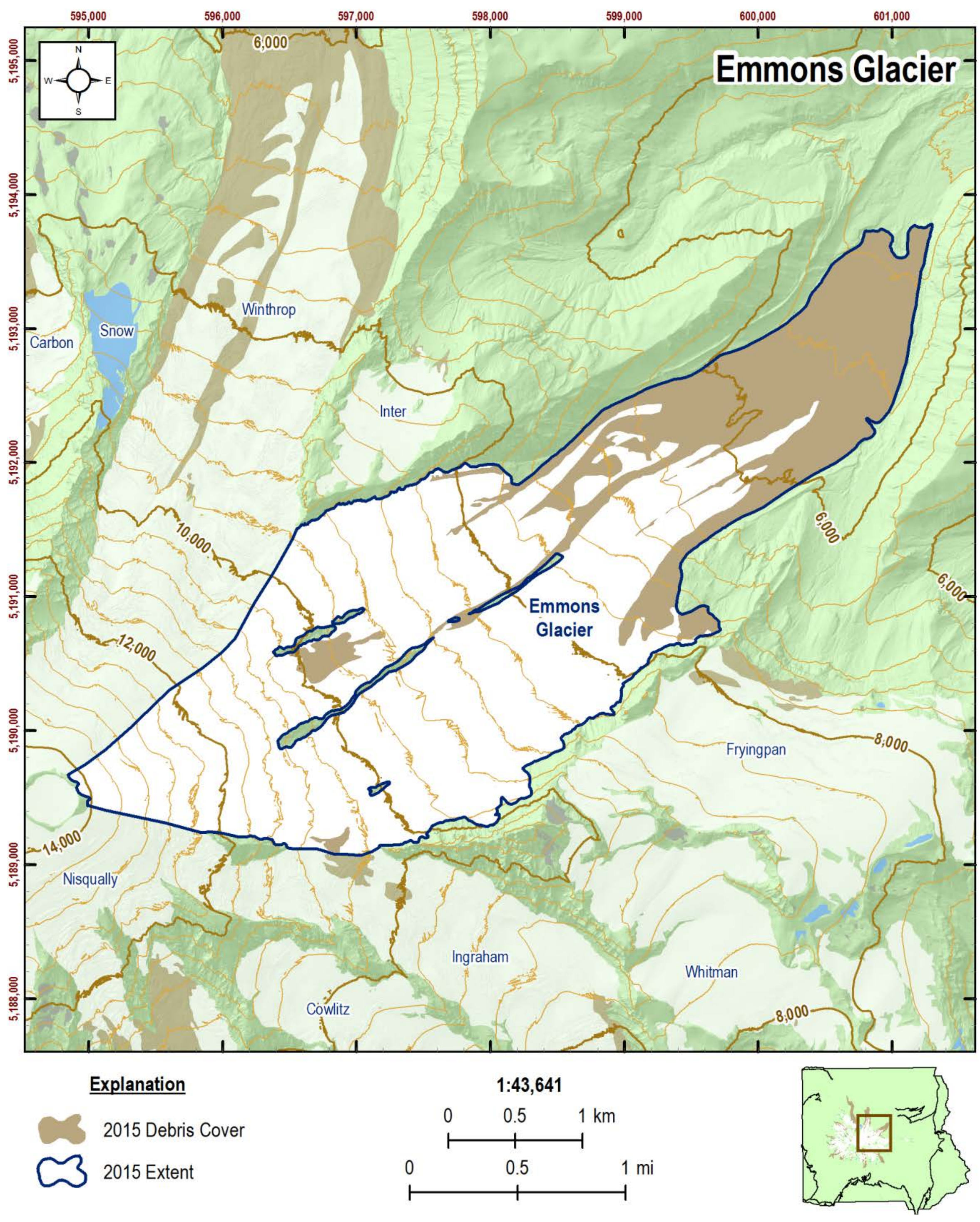
Glacier Name	Rank	2015 aerial extent of glacial ice m^2	km^2	mi^2	ac	Debris cover %	Rank
Cowlitz Glacier	7	3,990,333	3.990	1.541	986	36.03	6

Appendix A-5: Edmunds Glacier



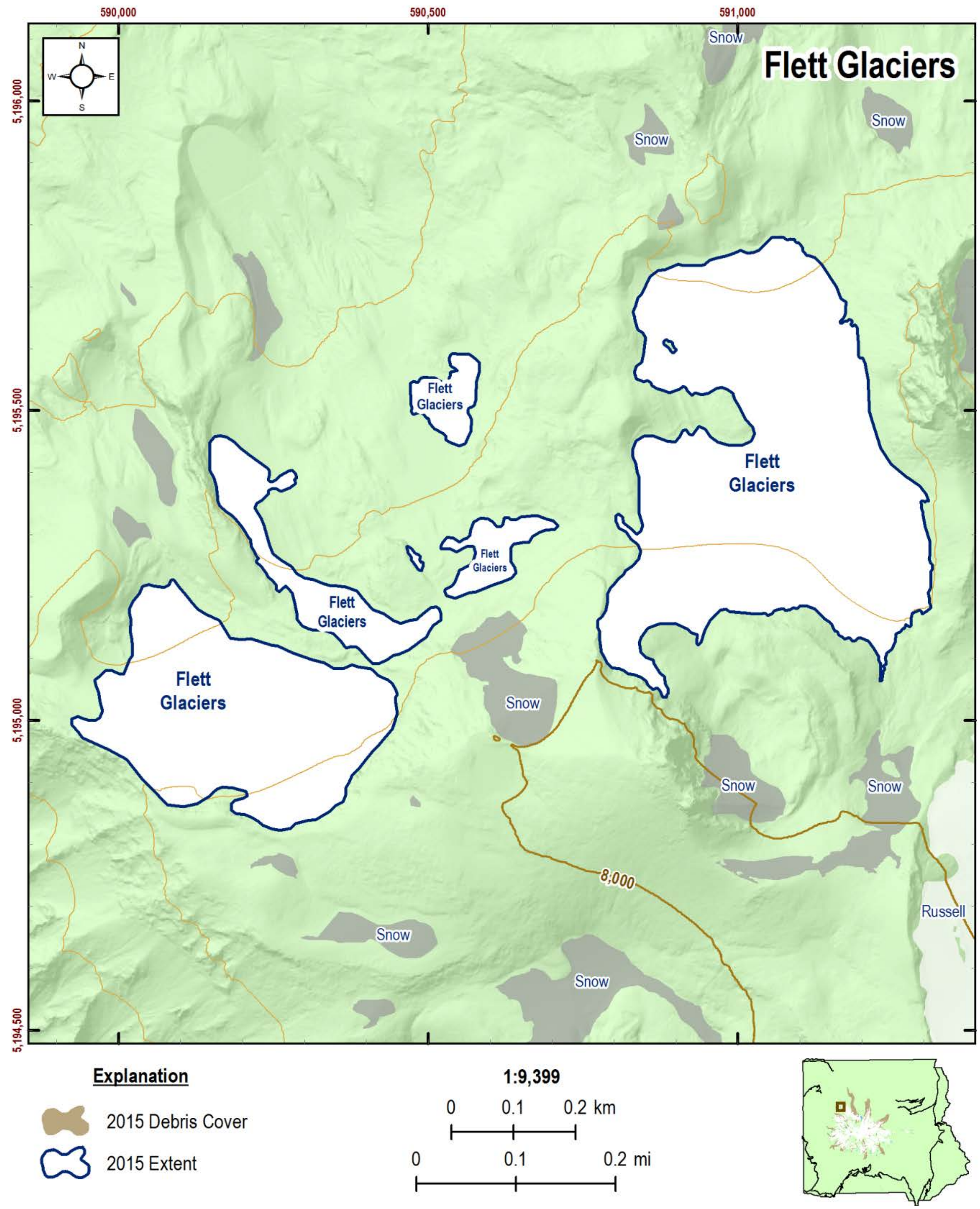
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Edmunds Glacier	18	1,252,436	1.252	0.484	309	10.39	14

Appendix A-6: Emmons Glacier



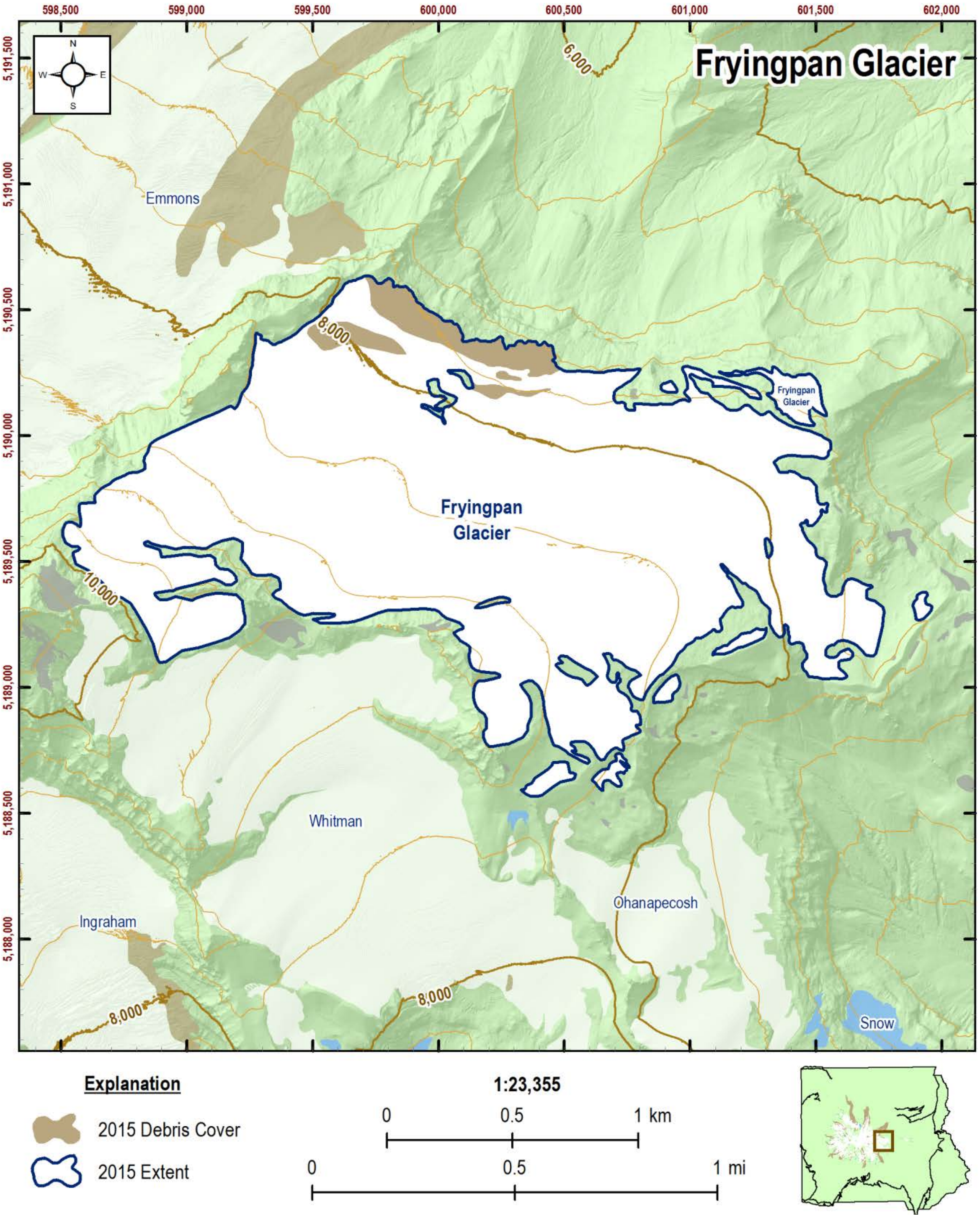
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Emmons Glacier	1	11,027,125	11.027	4.258	2,725	26.98	3

Appendix A-7: Flett Glaciers



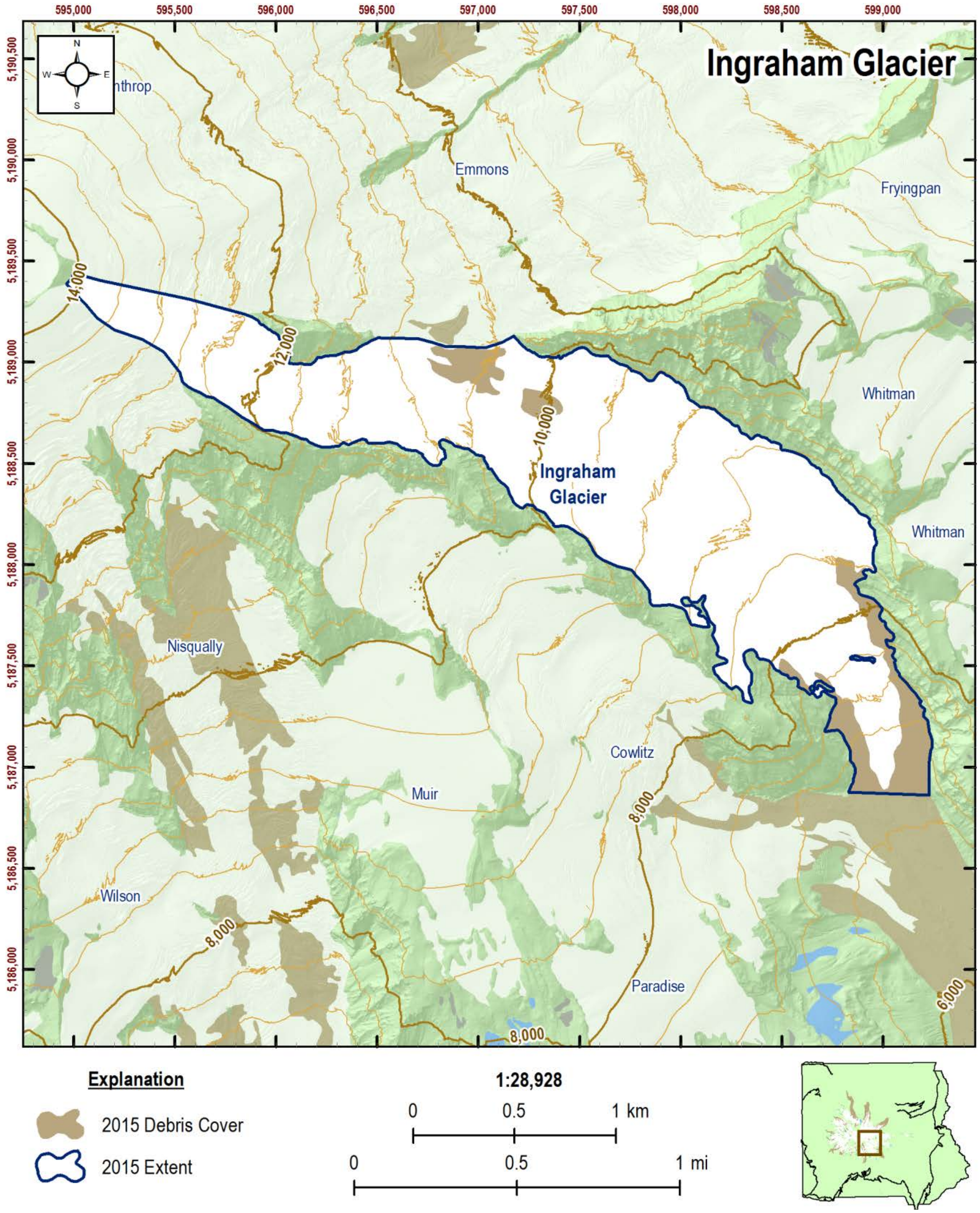
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Flett Glaciers	25	405,650	0.406	0.157	100	0	-

Appendix A-8: Fryingpan Glacier



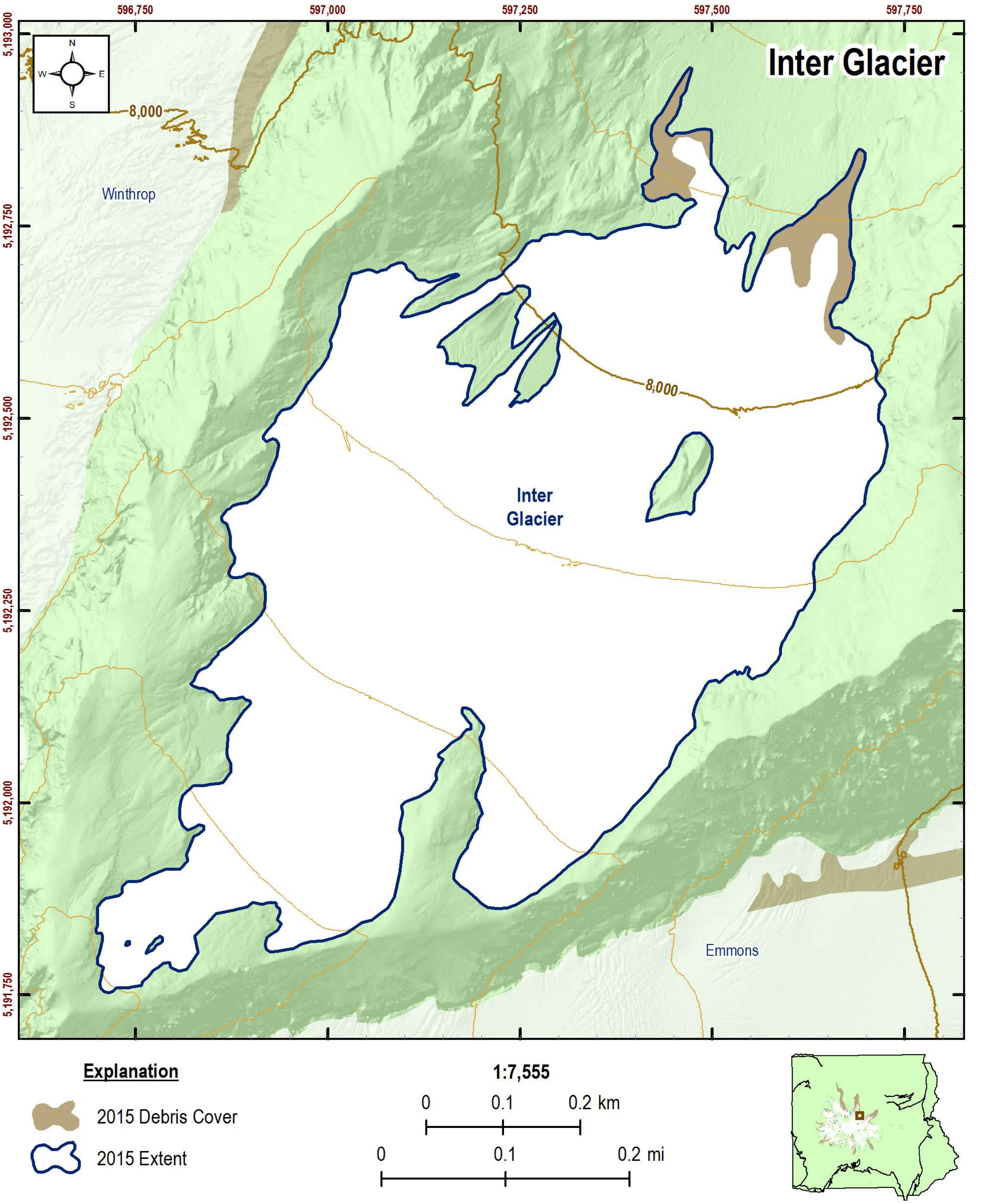
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Fryingpan Glacier	10	3,244,565	3.245	1.253	802	3.94	15

Appendix A-9: Ingraham Glacier



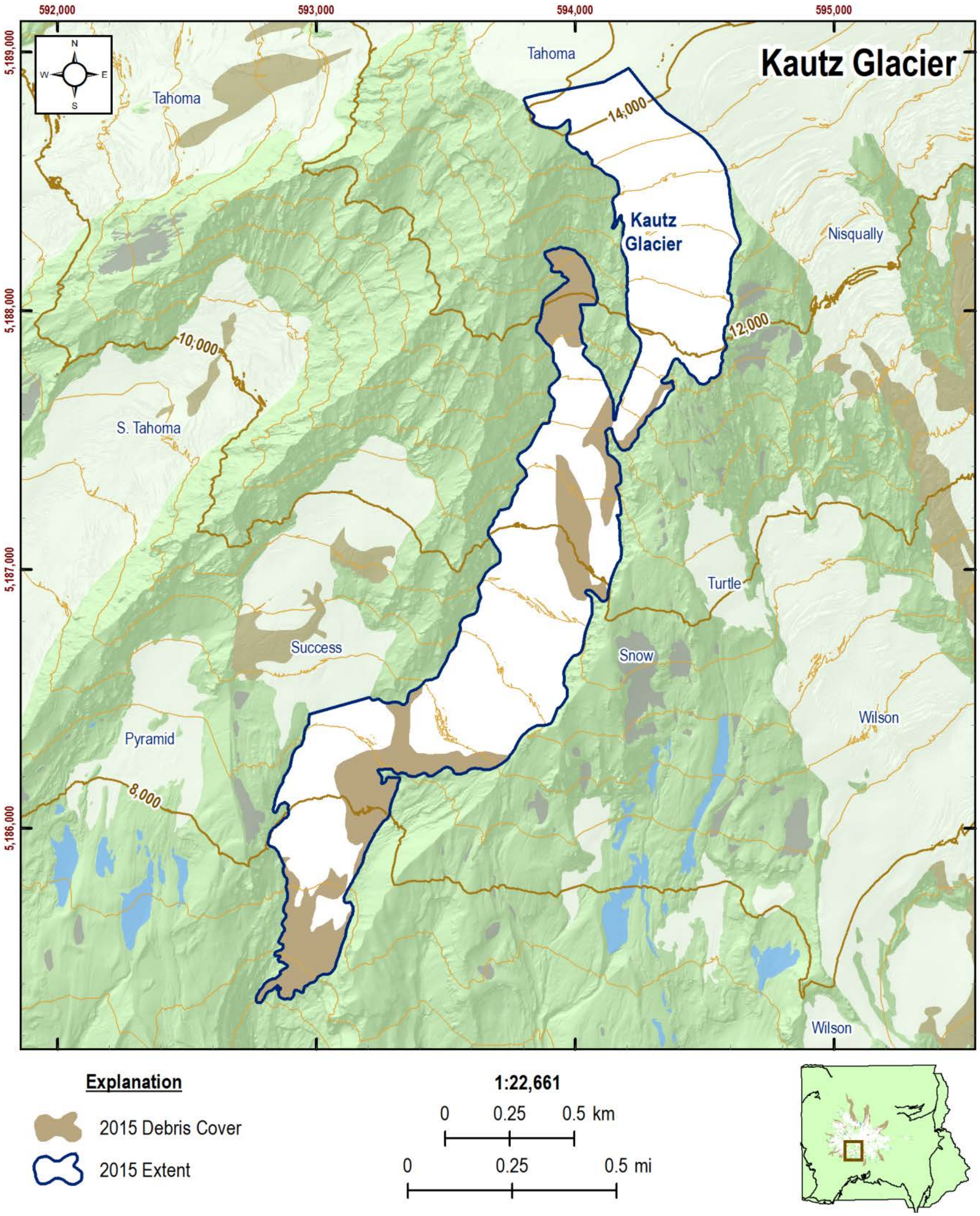
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Ingraham Glacier	11	3,007,289	3.007	1.161	743	9.17	12

Appendix A-10: Inter Glacier



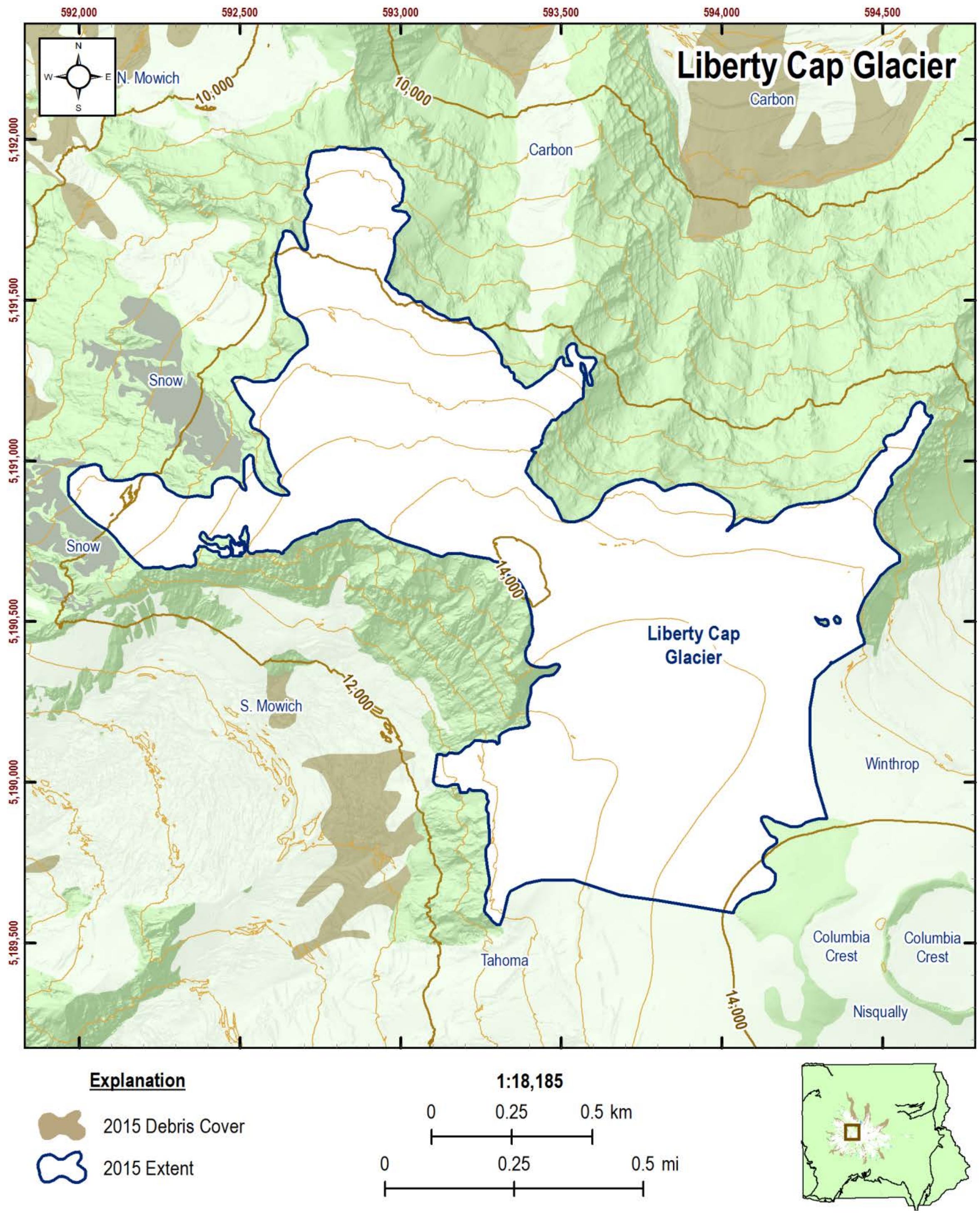
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Inter Glacier	22	573,974	0.574	0.222	142	2.60	18

Appendix A-11: Kautz Glacier



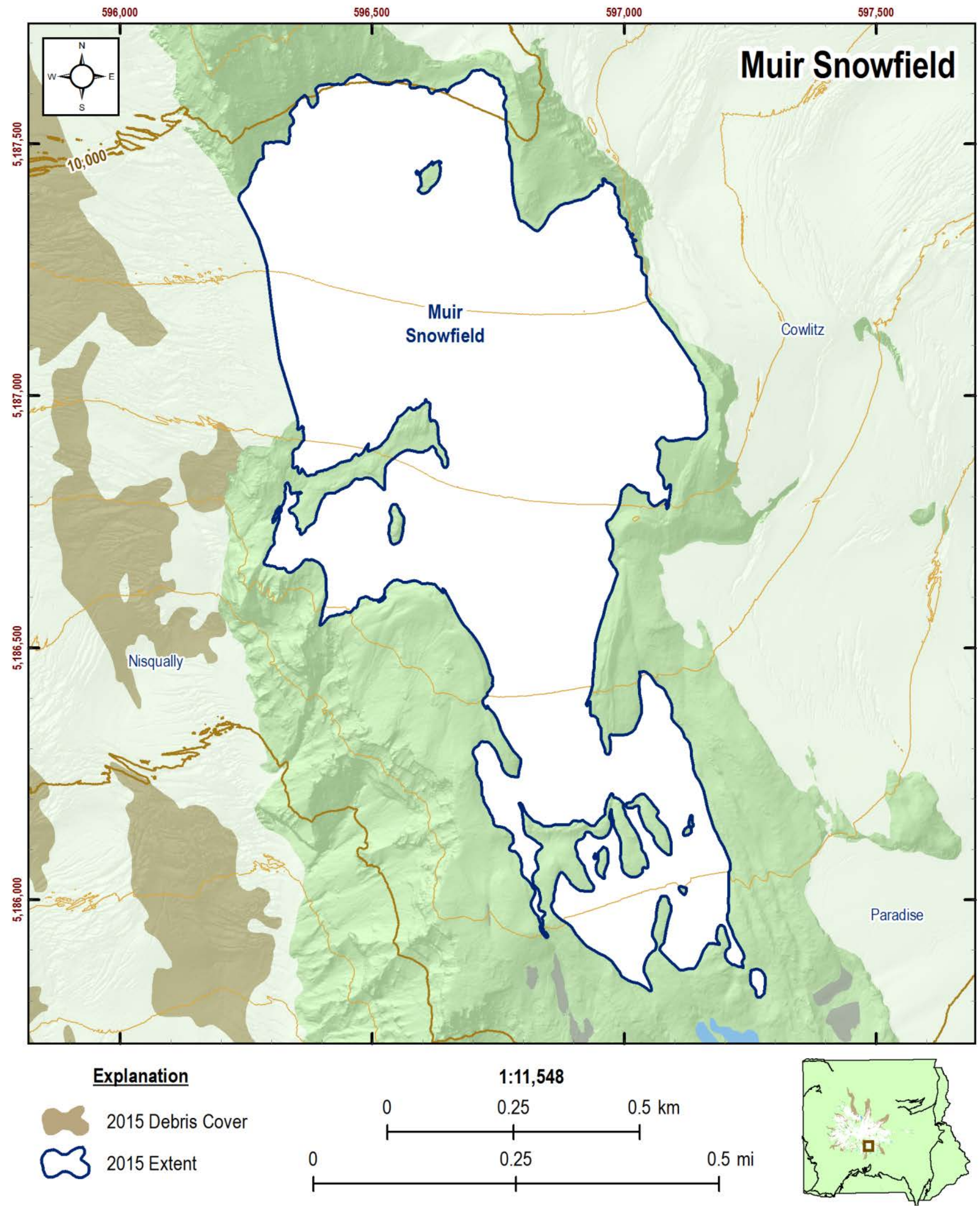
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Kautz Glacier	16	1,611,015	1.611	0.622	398	21.48	11

Appendix A-12: Liberty Cap Glacier



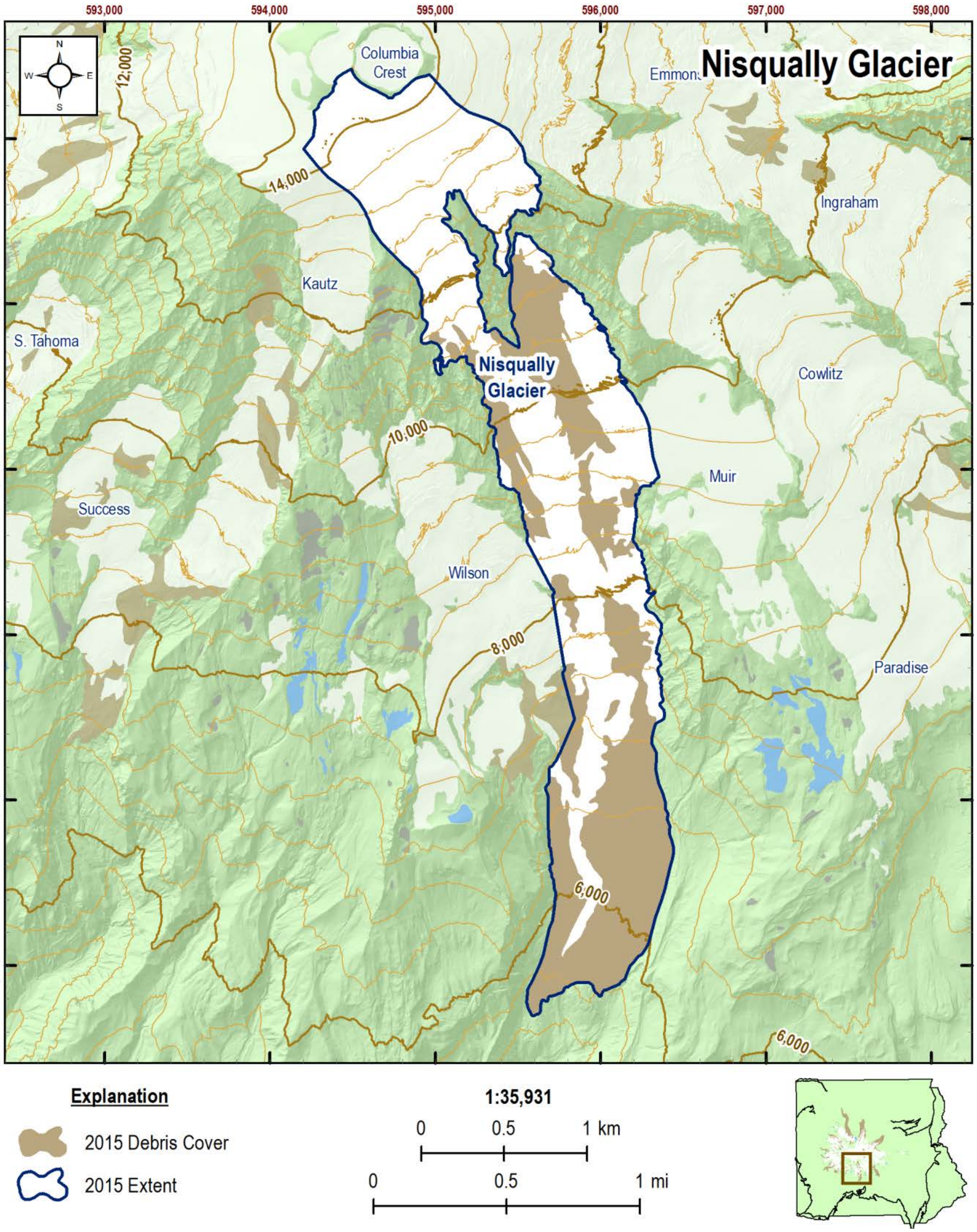
Glacier Name	Rank	2015 aerial extent of glacial ice m^2	km^2	mi^2	ac	Debris cover %	Rank
Carbon Glacier	13	2,138,709	2.139	0.826	528	0	-

Appendix A-13: Muir Snowfield



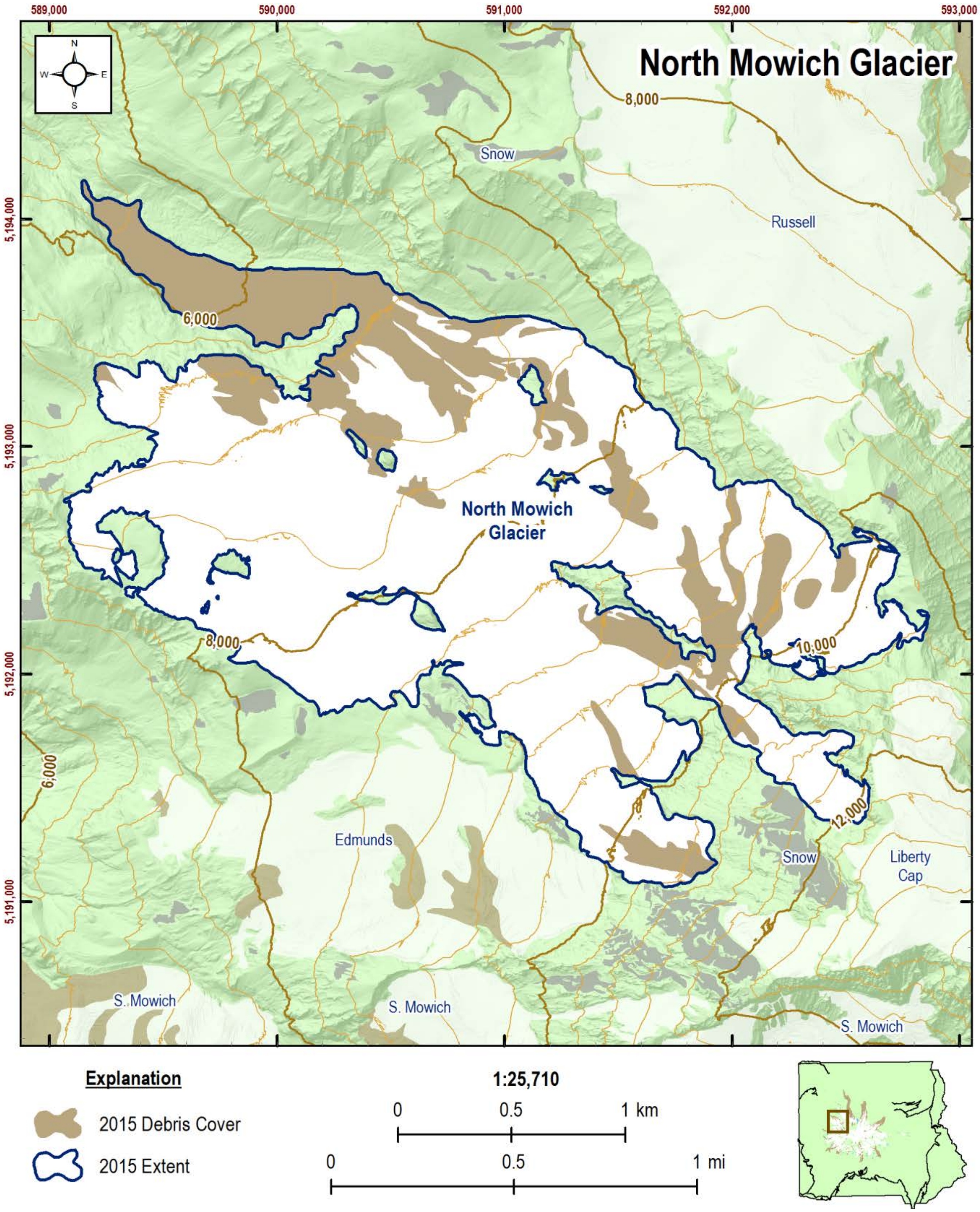
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Muir Snowfield	19	875,186	0.875	0.338	216	0	-

Appendix A-14: Nisqually Glacier



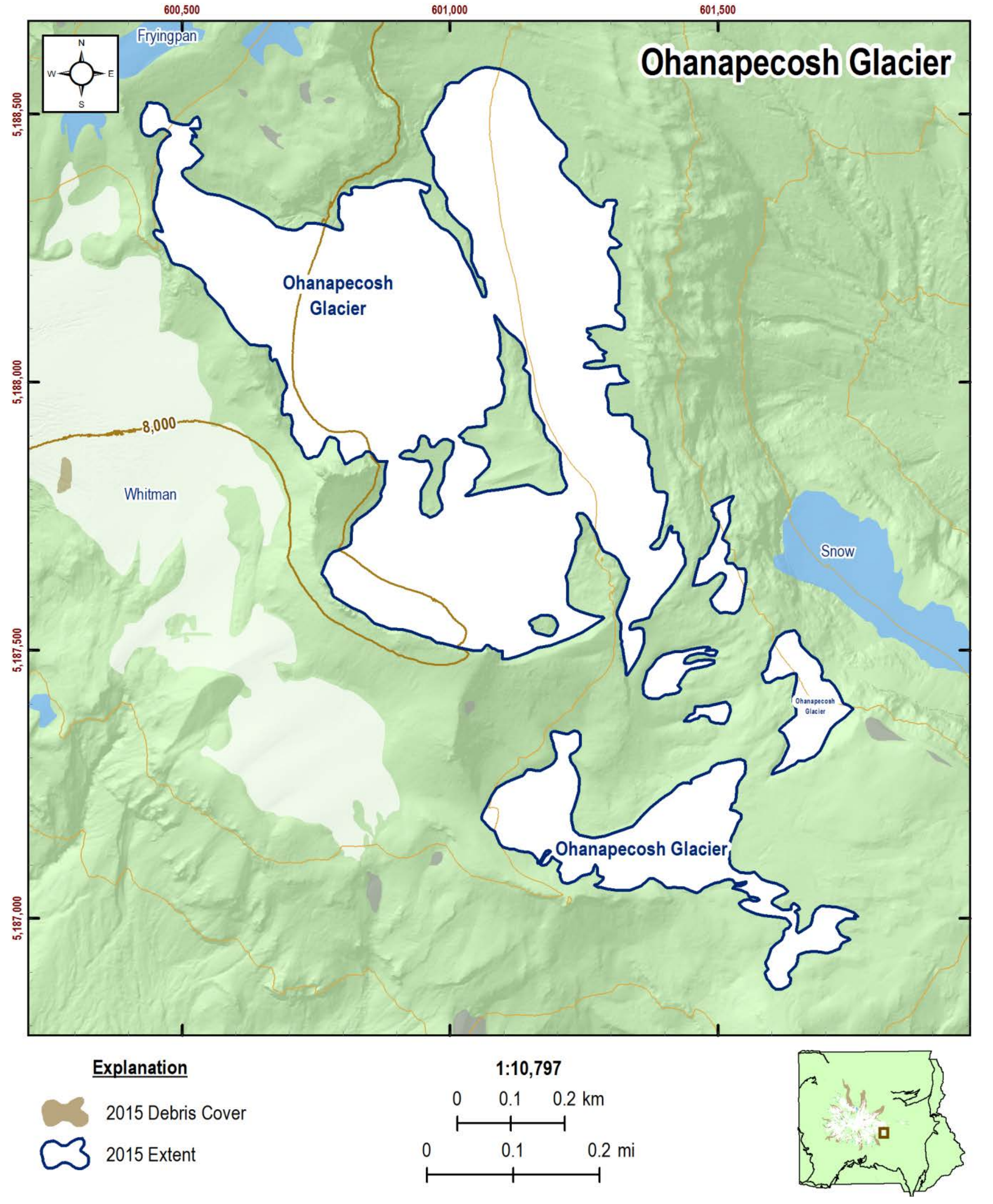
Glacier Name	Rank	2015 aerial extent of glacial ice m^2	km^2	mi^2	ac	Debris cover %	Rank
Nisqually Glacier	6	4,191,616	4.192	1.618	1,036	39.15	4

Appendix A-15: North Mowich Glacier



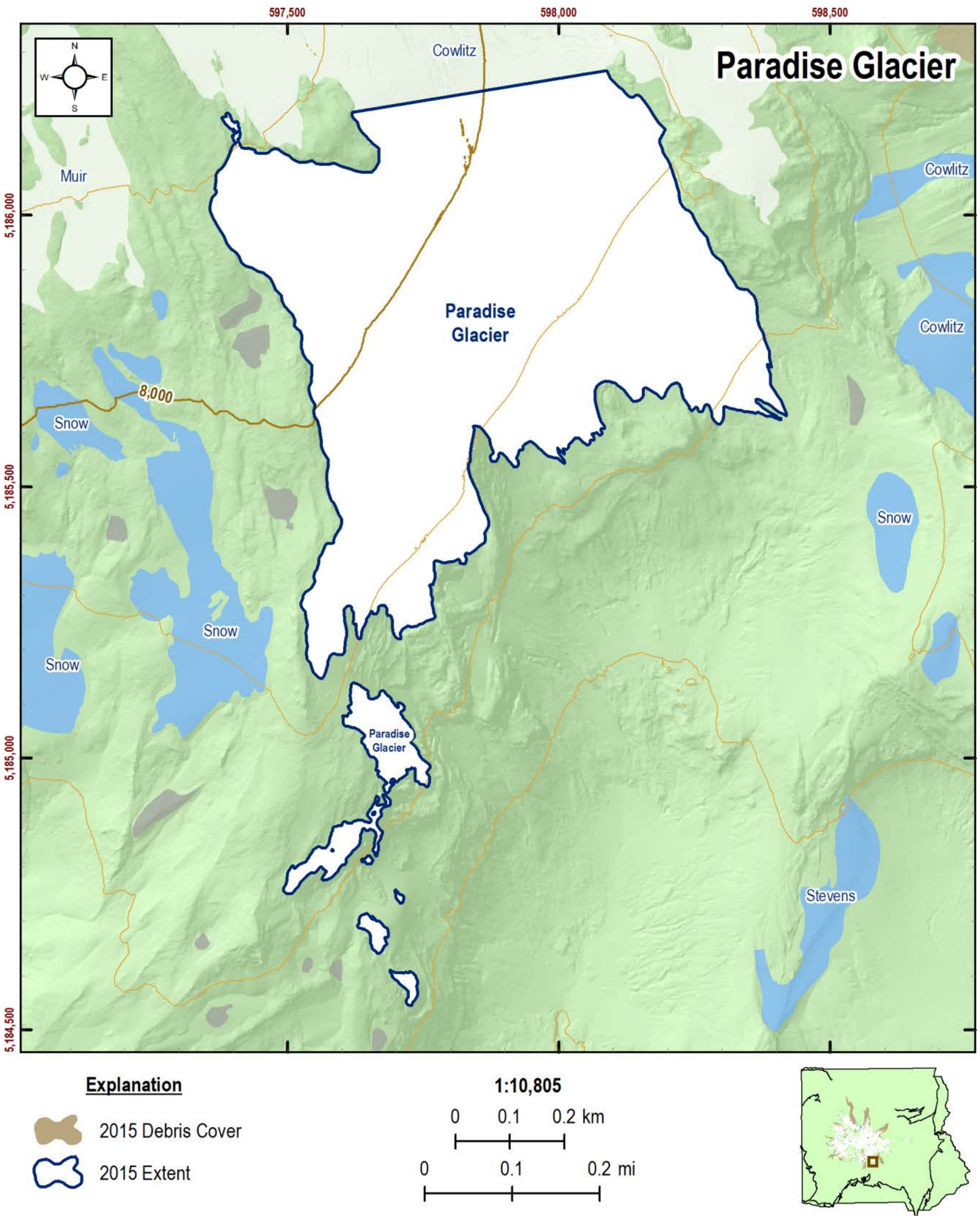
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	**Rank**	**m^2**	**km^2**	**mi^2**	**ac**	**%**	**Rank**
North Mowich Glacier	5	5,144,280	5.144	1.986	1,271	21.66	7

Appendix A-16: Ohanapecosh Glacier



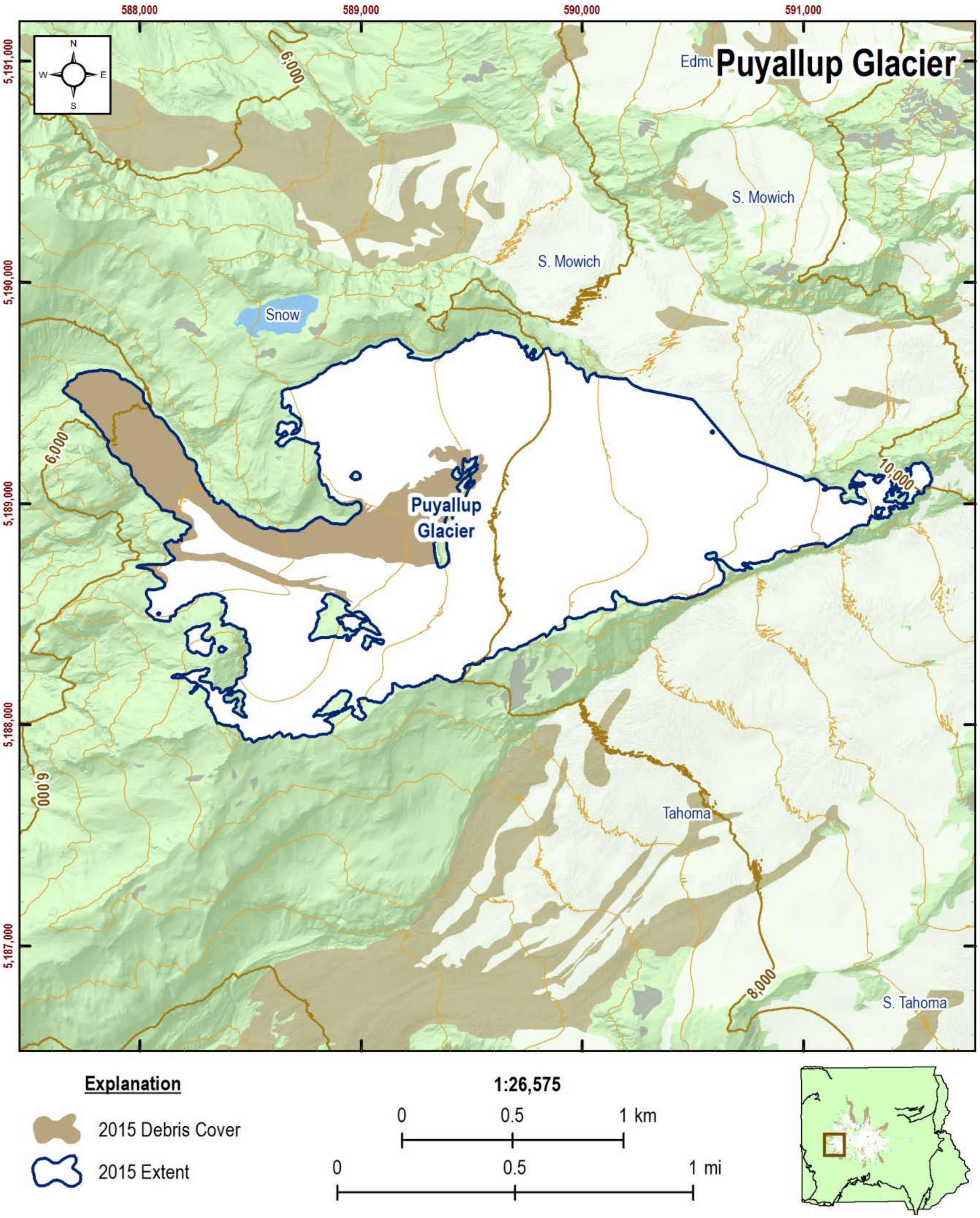
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Ohanapecosh Glacier	20	668,974	0.669	.258	165	0	-

Appendix A-17: Paradise Glacier



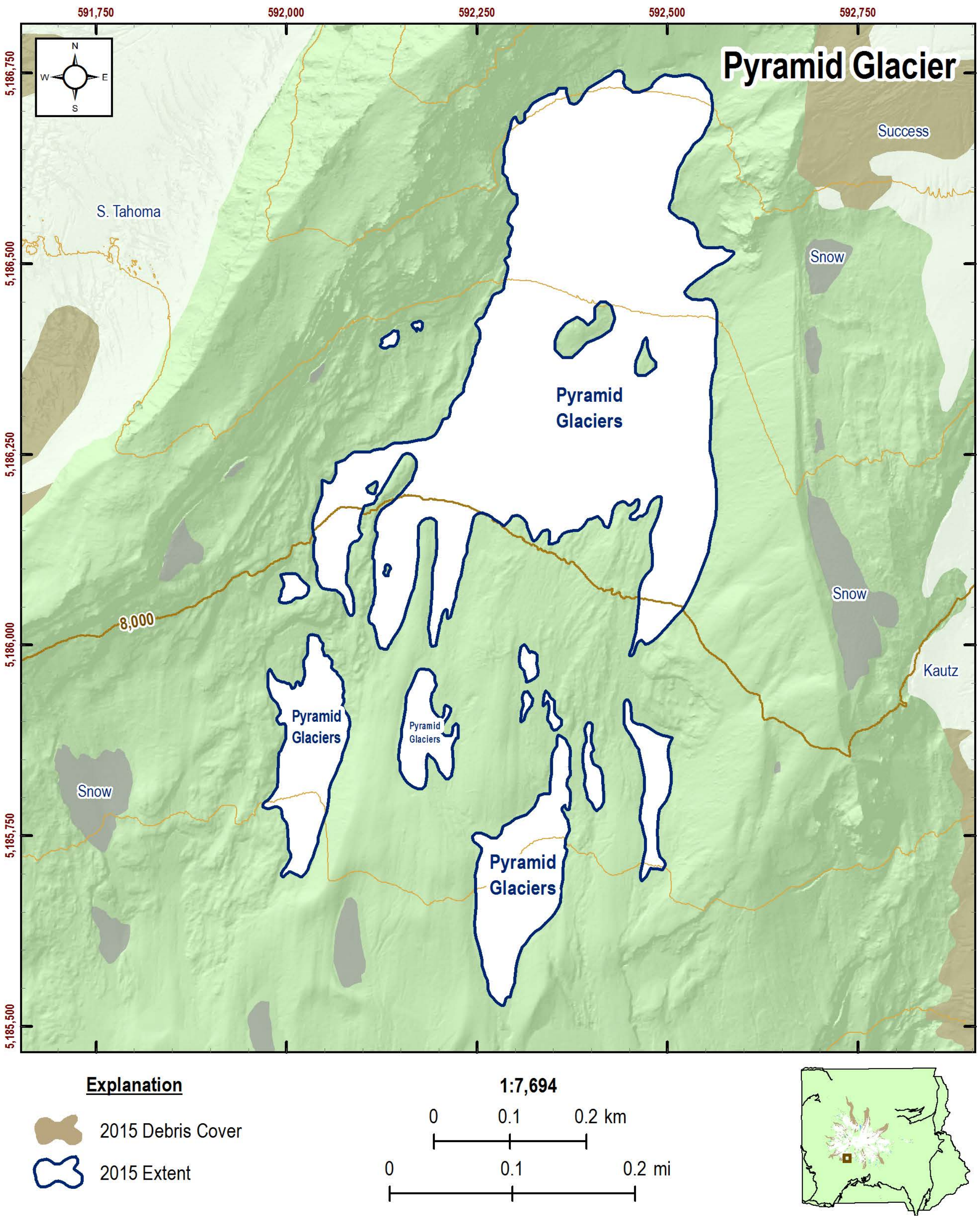
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Paradise Glacier	21	611,832	0.612	0.236	151	0	-

Appendix A-18: Puyallup Glacier



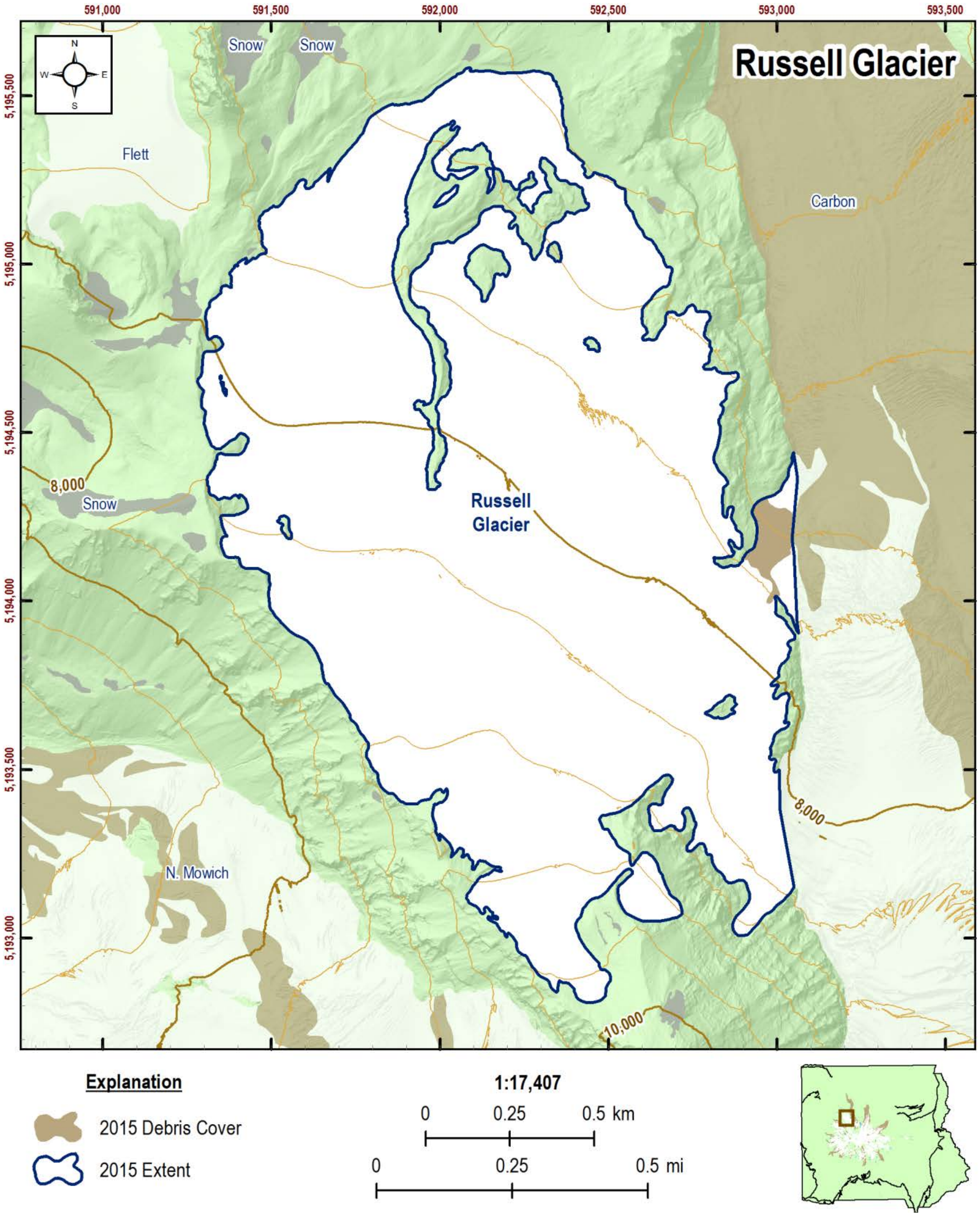
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Puyallup Glacier	9	3,257,836	3.258	1.258	805	14.29	10

Appendix A-19: Pyramid Glacier



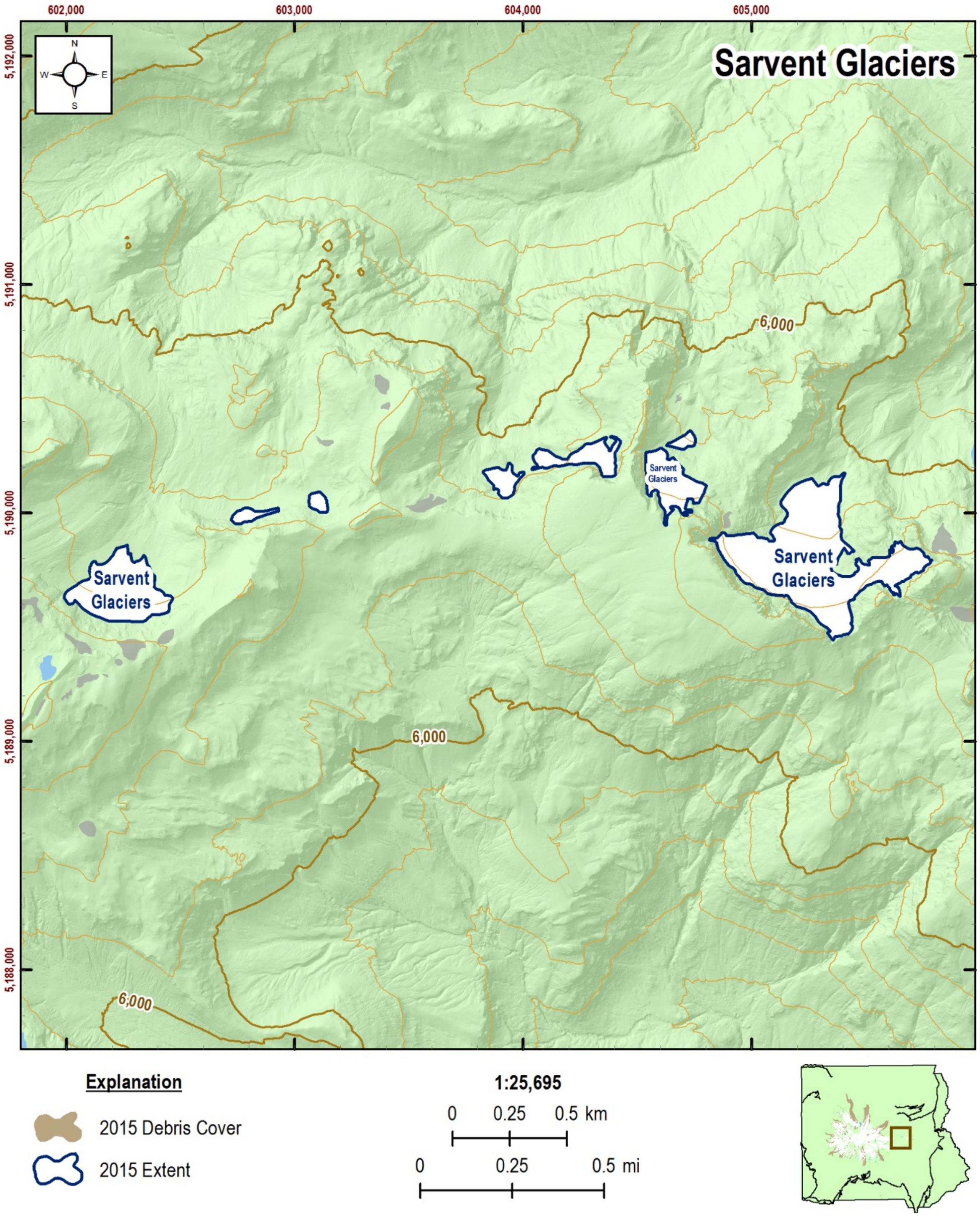
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Pyramid Glacier	26	262,231	0.262	0.101	65	0	-

Appendix A-20: Russell Glacier



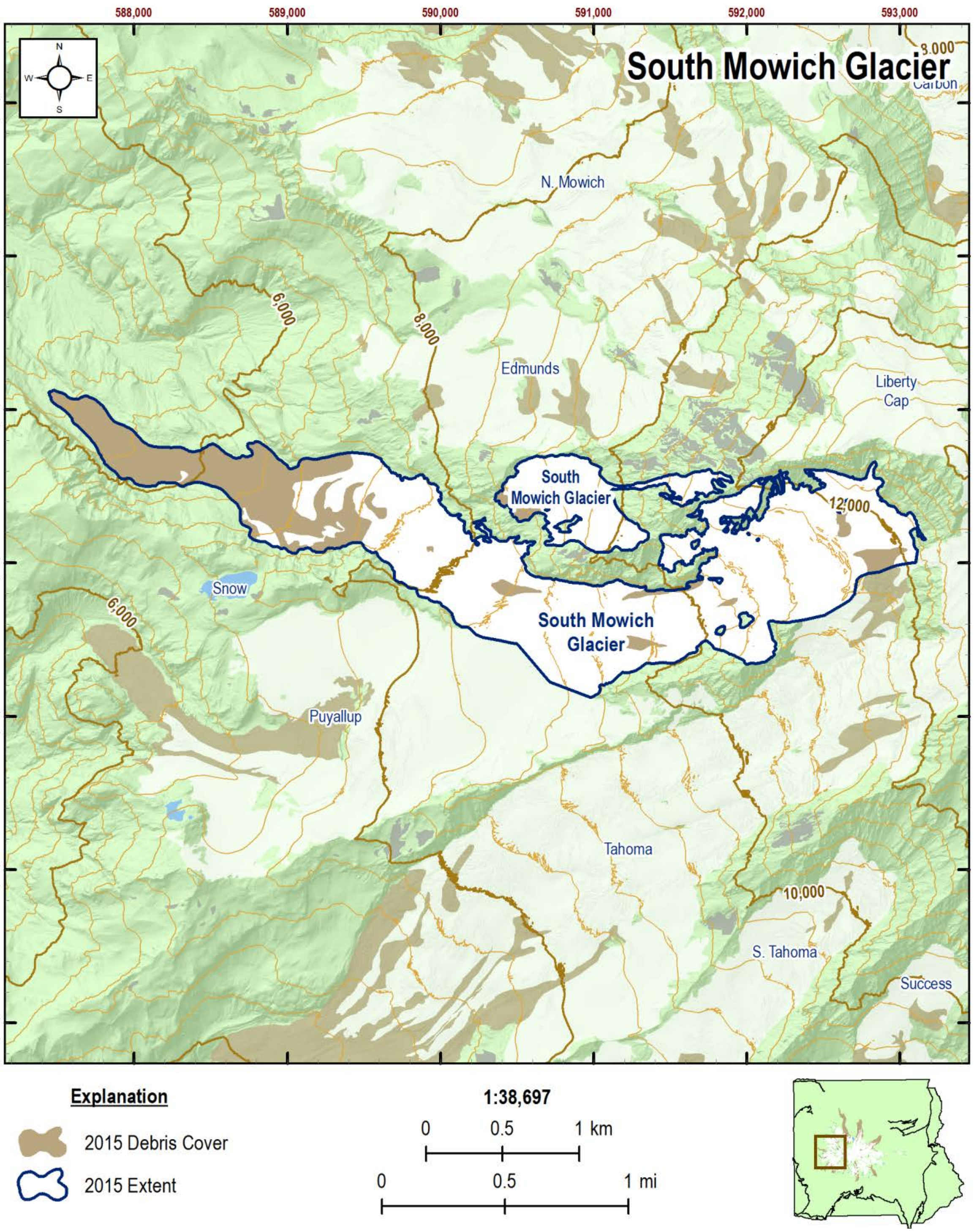
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Russell Glacier	12	2,892,409	2.892	1.117	715	0.79	17

Appendix A-21: Sarvent Glaciers



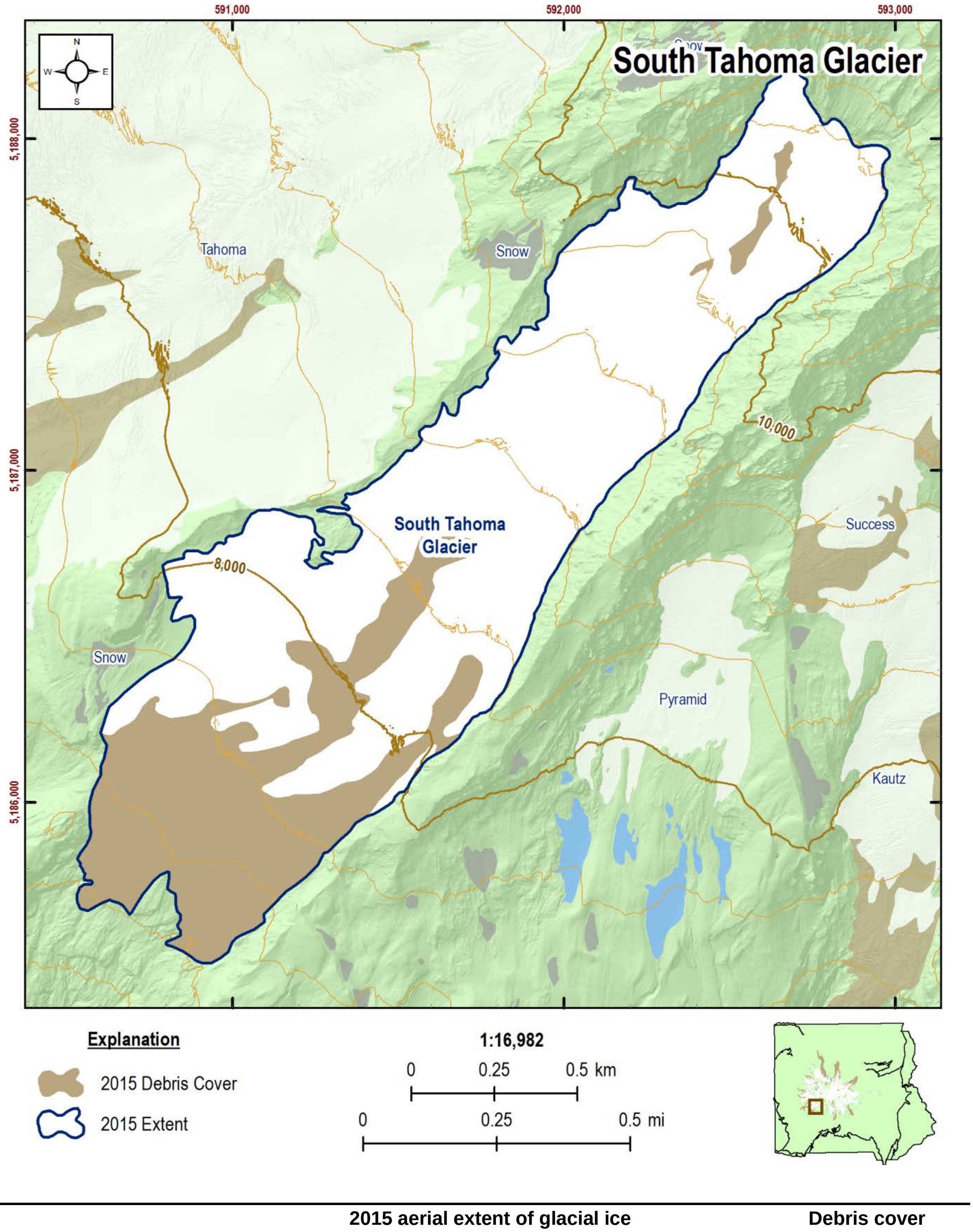
Glacier Name	Rank	2015 aerial extent of glacial ice m²	km²	mi²	ac	Debris cover %	Rank
Sarvent Glaciers	24	454,659	0.455	0.176	112	0	-

Appendix A-22: South Mowich Glacier



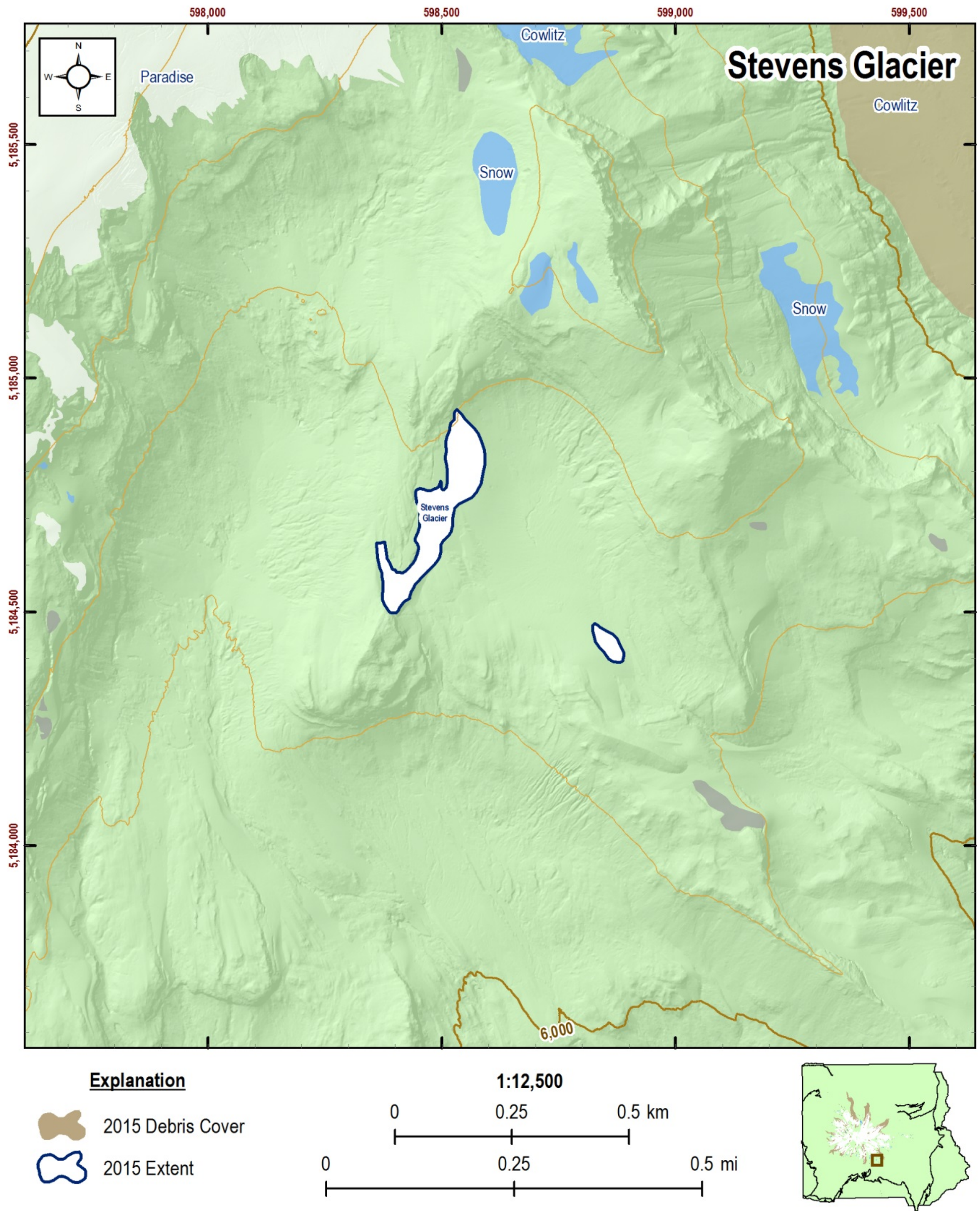
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
South Mowich Glacier	8	3,765,553	3.766	1.454	930	20.93	8

Appendix A-23: South Tahoma Glacier



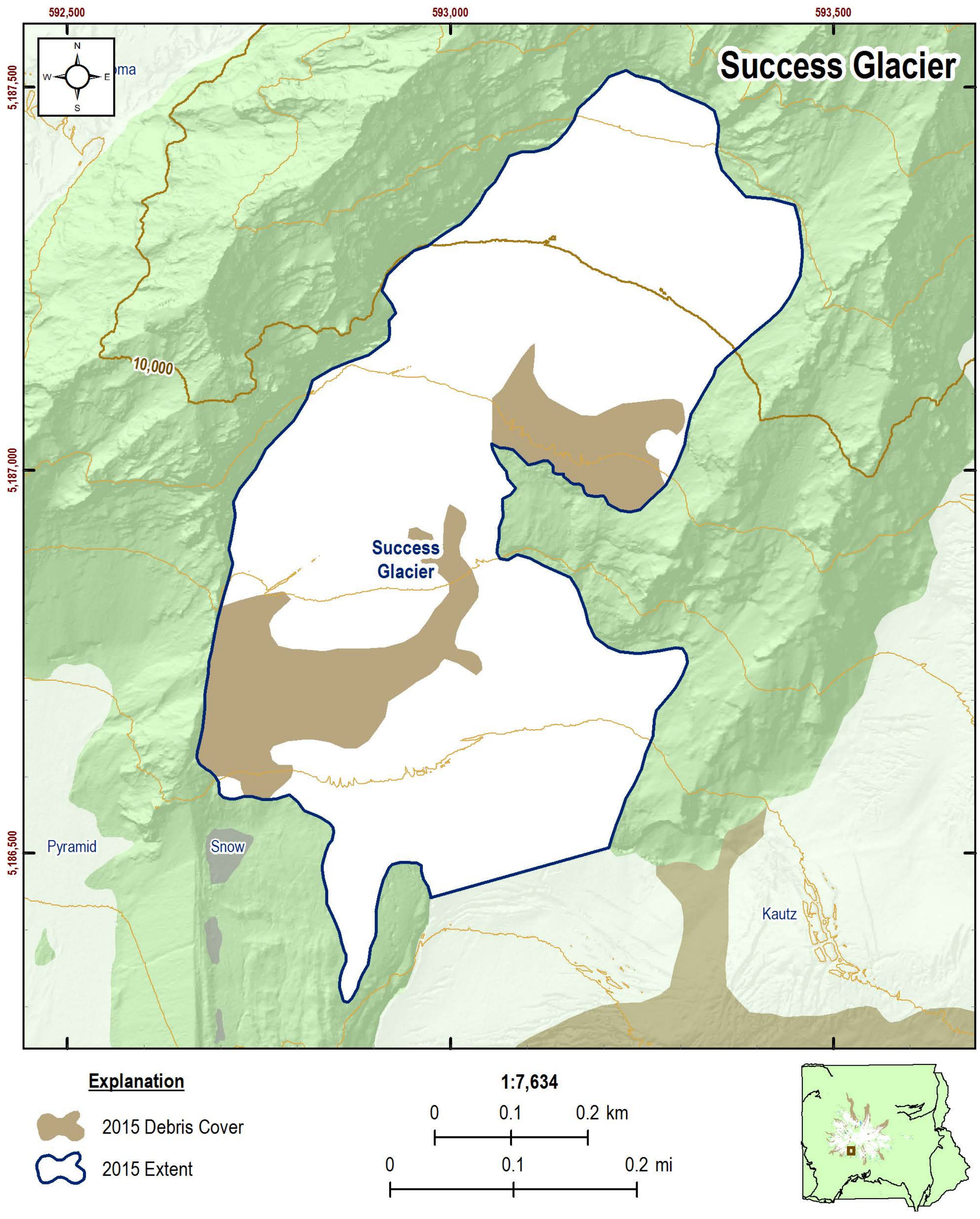
Glacier Name	Rank	2015 aerial extent of glacial ice m^2	km^2	mi^2	ac	Debris cover %	Rank
South Tahoma Glacier	14	2,001,825	2.002	0.773	495	27.81	9

Appendix A-24: Stevens Glacier



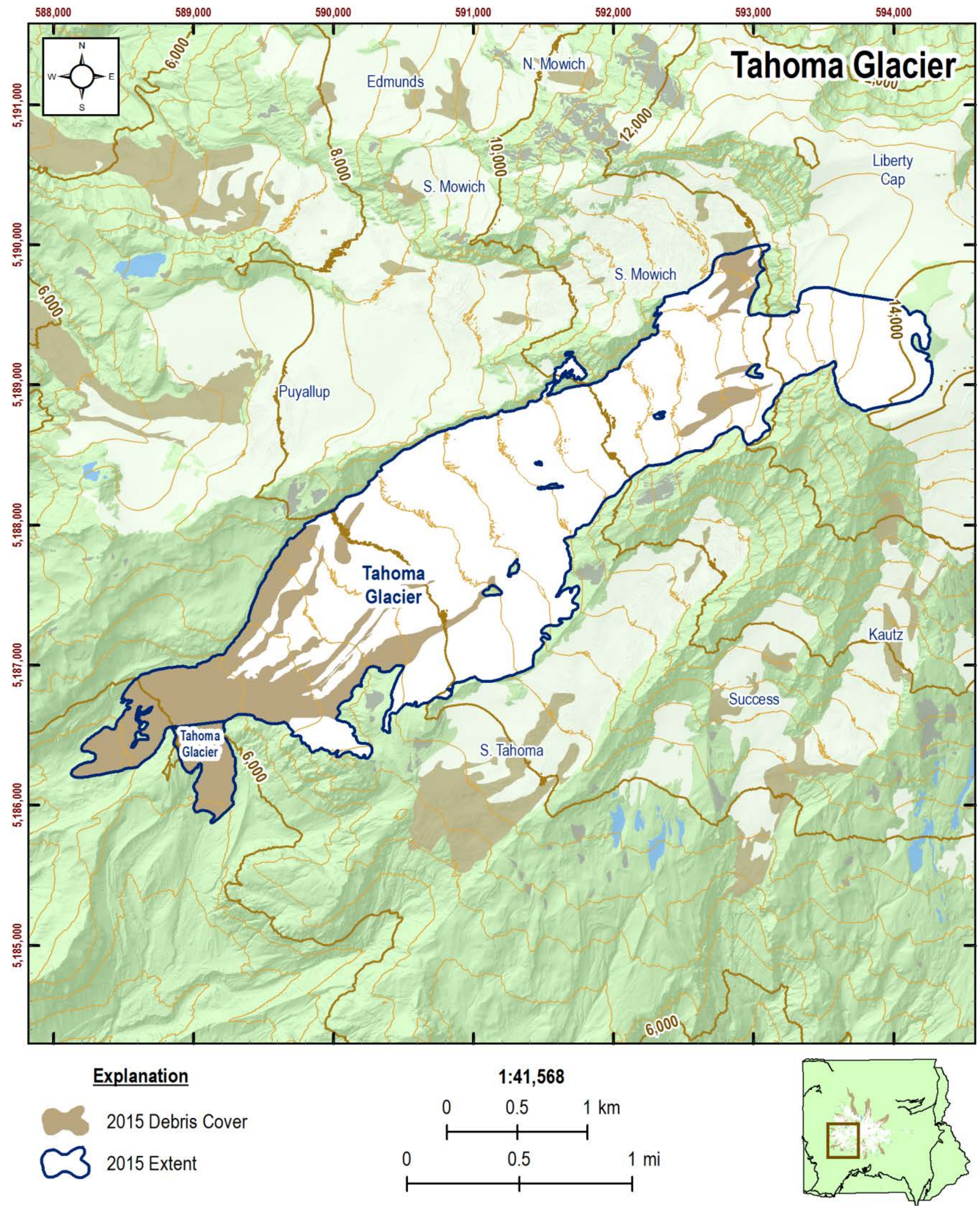
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Stevens Glacier	29	33,139	0.033	0.013	8	0	-

Appendix A-25: Success Glacier



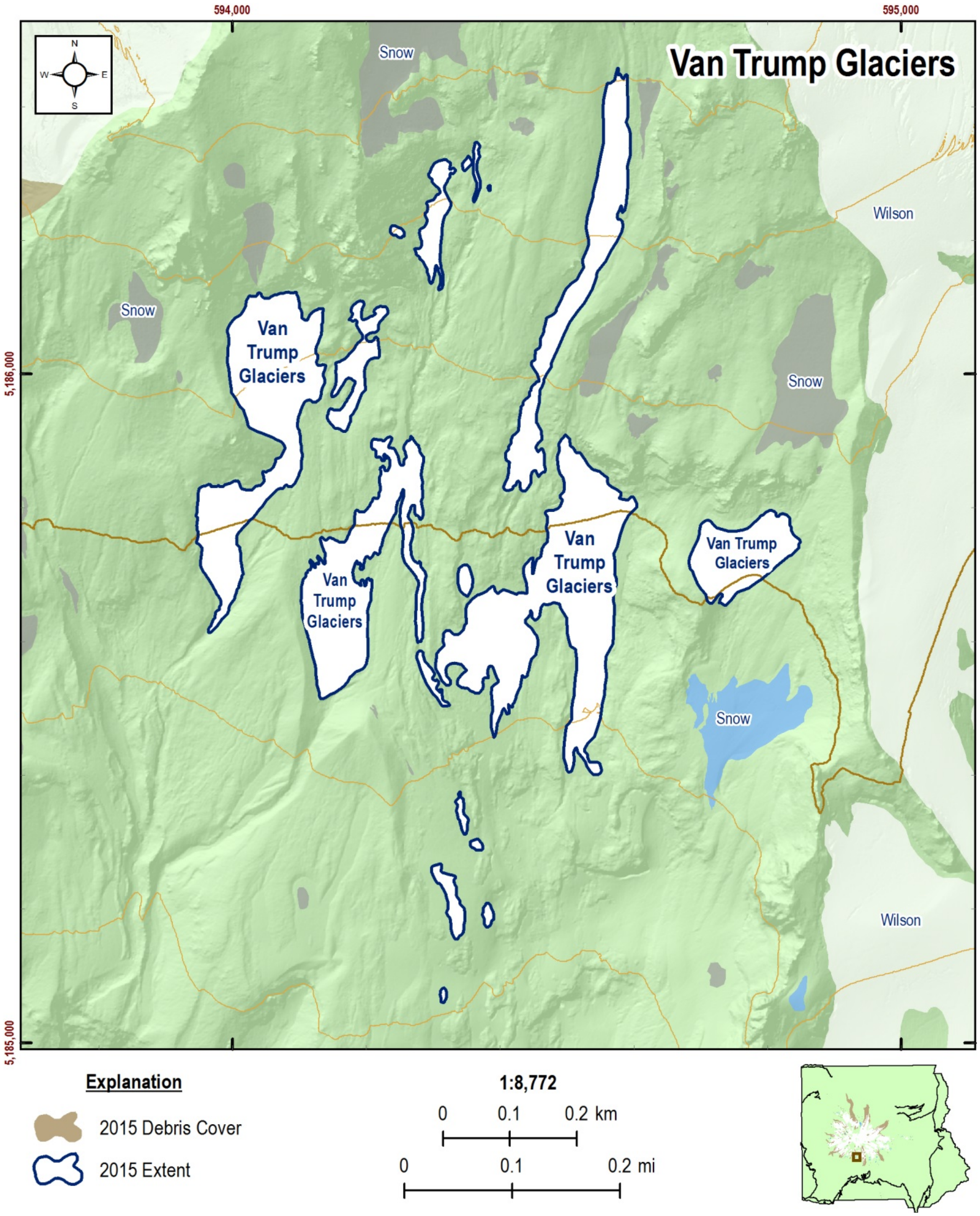
Glacier Name	Rank	2015 aerial extent of glacial ice m^2	km^2	mi^2	ac	Debris cover %	Rank
Success Glacier	23	469,850	0.470	0.181	116	16.63	16

Appendix A-26: Tahoma Glacier



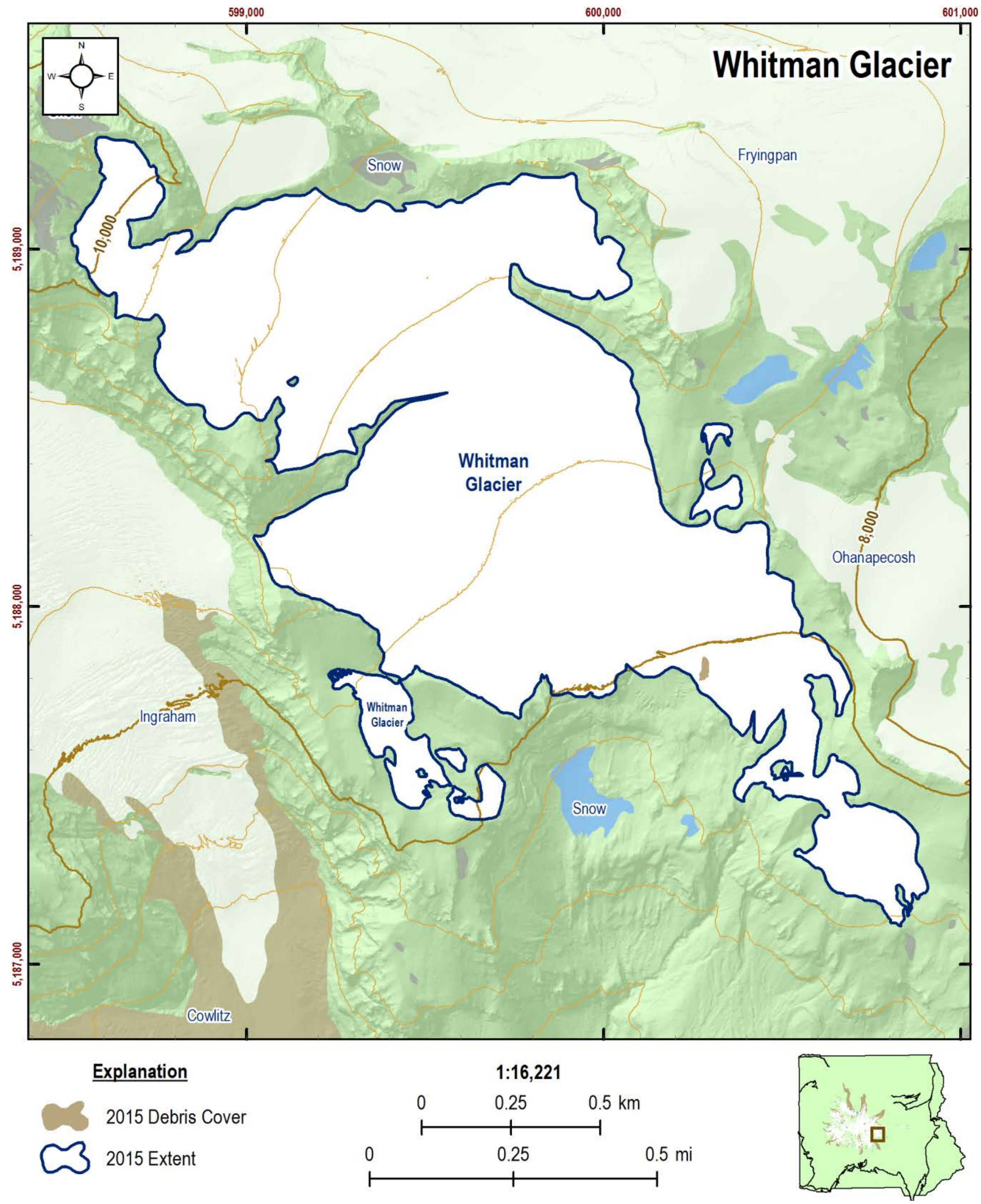
Glacier Name	Rank	2015 aerial extent of glacial ice m^2	km^2	mi^2	ac	Debris cover %	Rank
Tahoma Glacier	4	6,787,052	6.787	2.620	1,677	22.99	5

Appendix A-27: Van Trump Glaciers



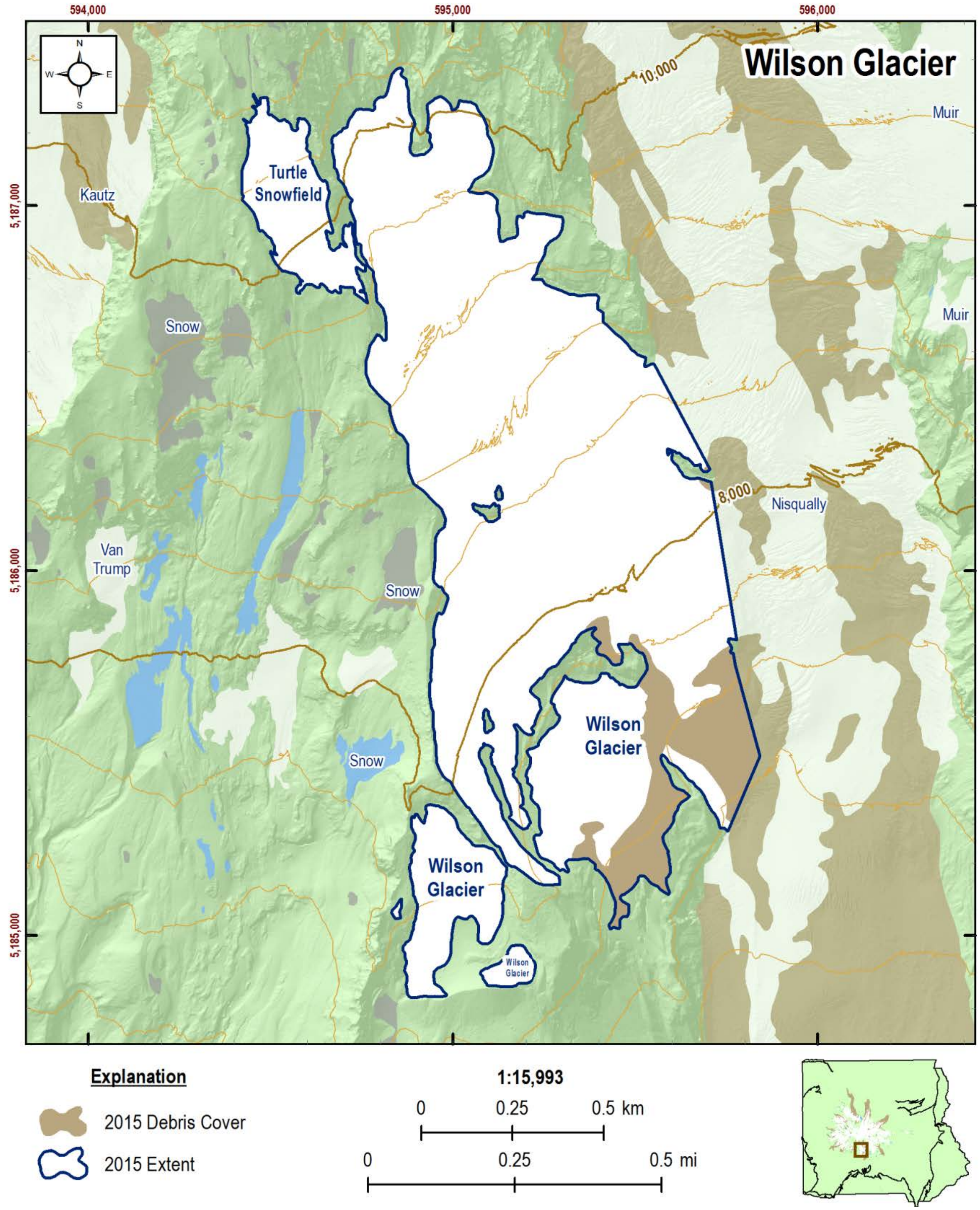
Glacier Name	Rank	2015 aerial extent of glacial ice m^2	km^2	mi^2	ac	Debris cover %	Rank
Van Trump Glaciers	28	175,927	0.176	0.068	43	0	-

Appendix A-28: Whitman Glacier



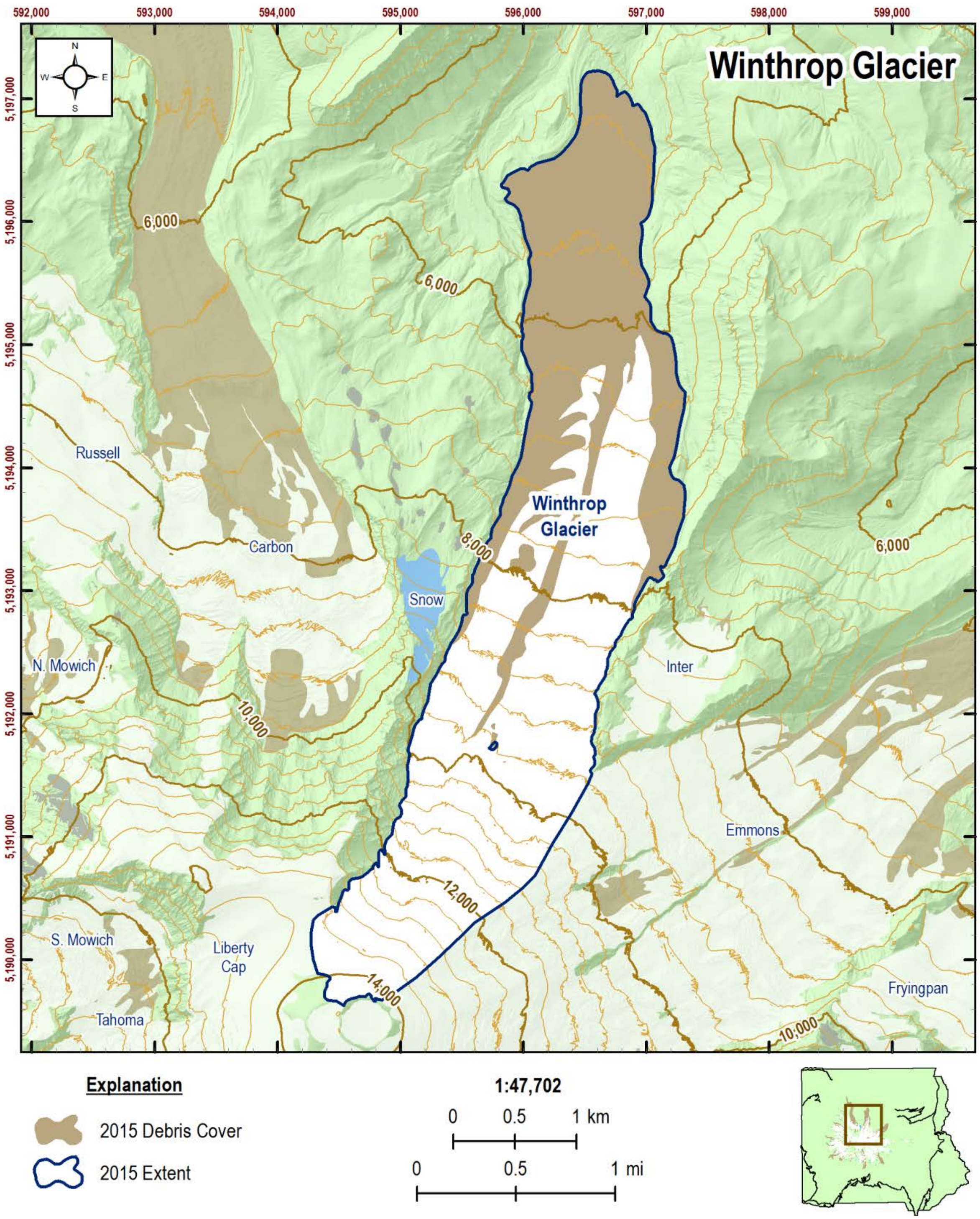
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	**Rank**	**m²**	**km²**	**mi²**	**ac**	**%**	**Rank**
Whitman Glacier	15	1,938,793	1.939	0.749	479	0.07	19

Appendix A-29: Wilson Glacier



		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Wilson Glacier	17	1,562,401	1.562	0.603	386	8.50	13

Appendix A-30: Winthrop Glacier



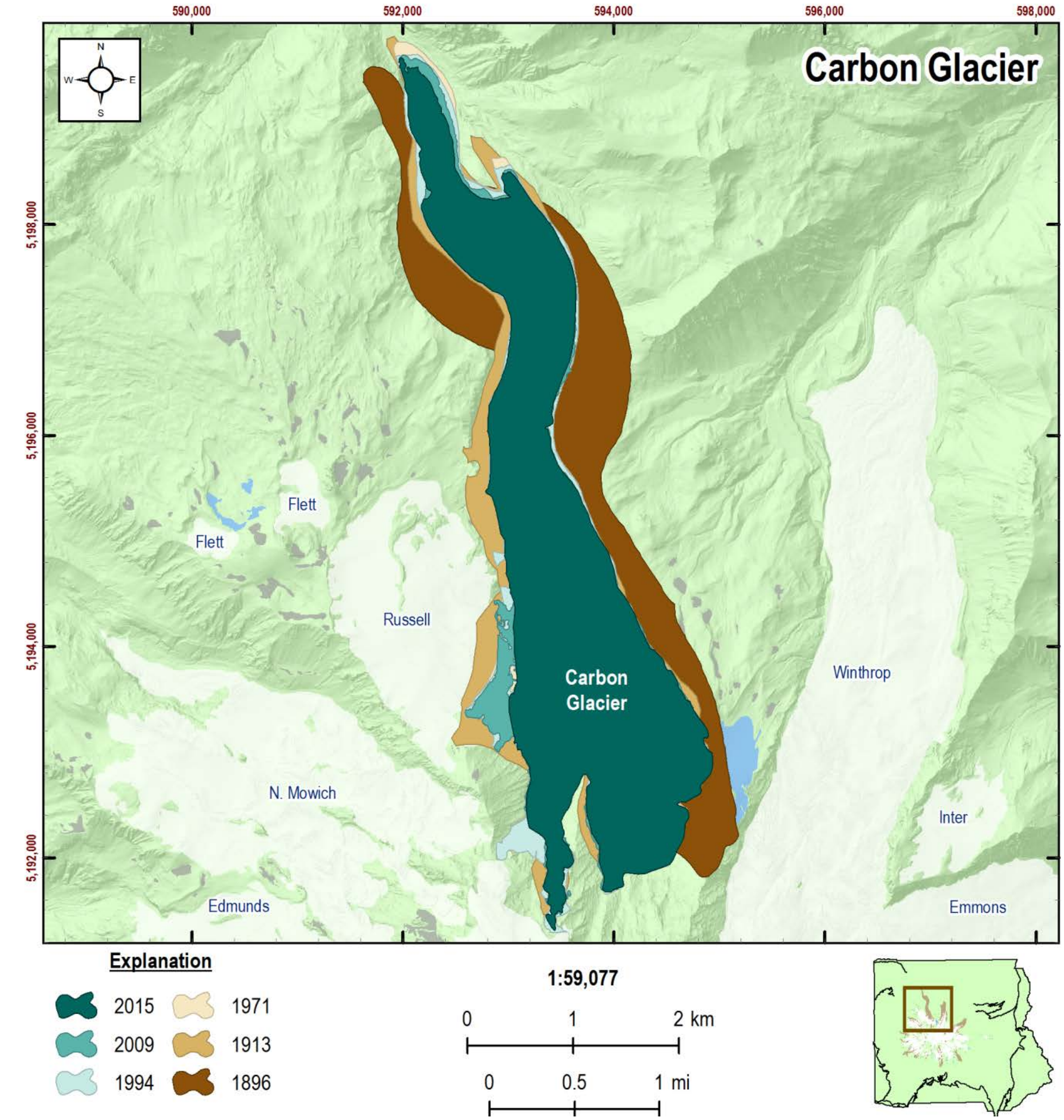
		2015 aerial extent of glacial ice				Debris cover	
Glacier Name	Rank	m^2	km^2	mi^2	ac	%	Rank
Winthrop Glacier	2	8,976,552	8.977	3.466	2,218	38.92	2

Appendix B: Detail maps of individual named glaciers with change over time at Mount Rainier

Notes for all maps:

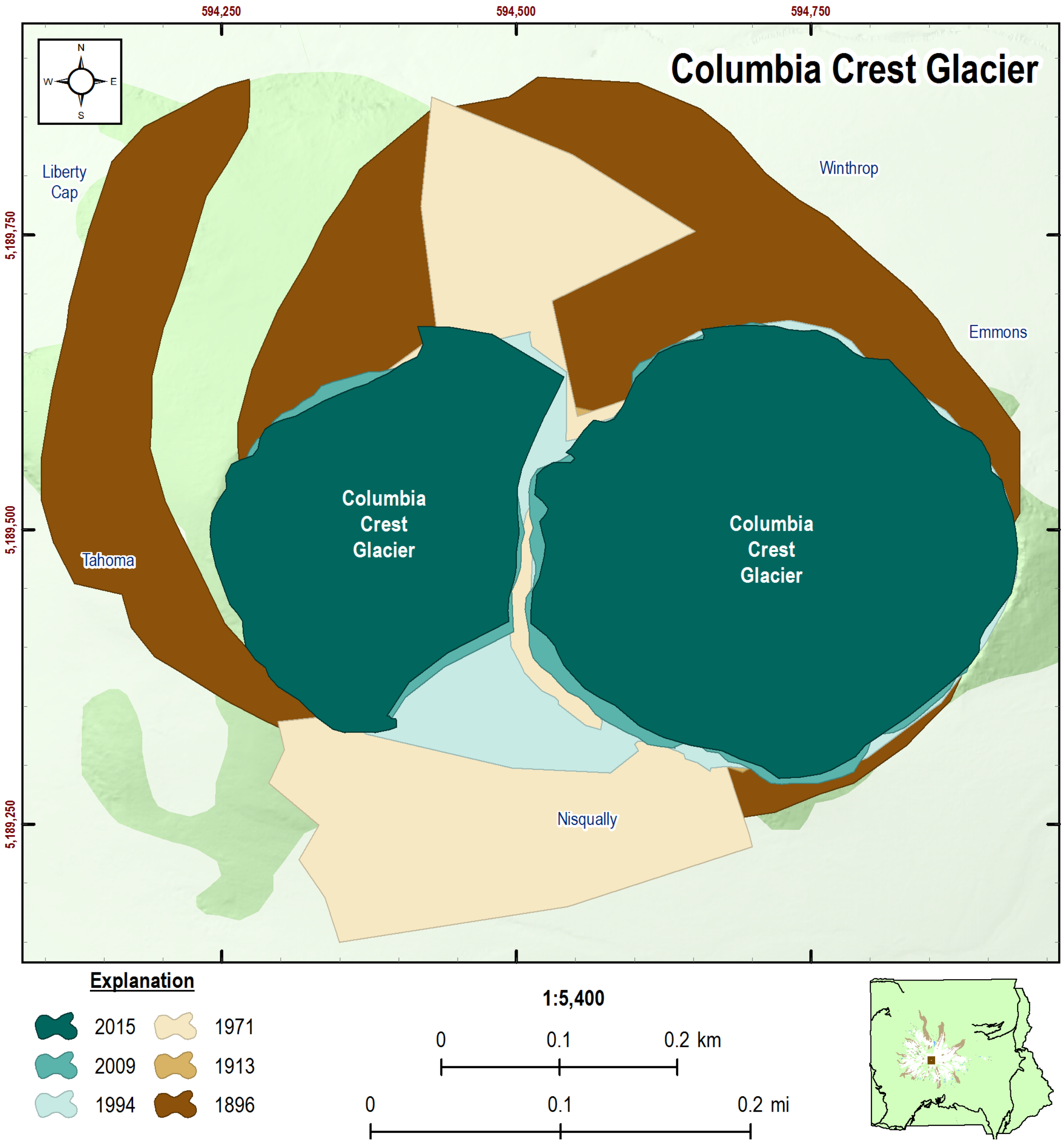
- Map grids are plotted in NAD 1983 UTM Zone 10 North (meters)
- Background hill shade based on 2007/8 LiDAR Survey
- Aerial extent of glaciers is from Table 4.
- Change in extent of glaciers is from Tables 5 and 6.

A large format map (ANSI-E; 34x44 in) encompassing the full park area is available separately (https://irma.nps.gov/DataStore/Reference/Profile/2242142) as Plate 2.



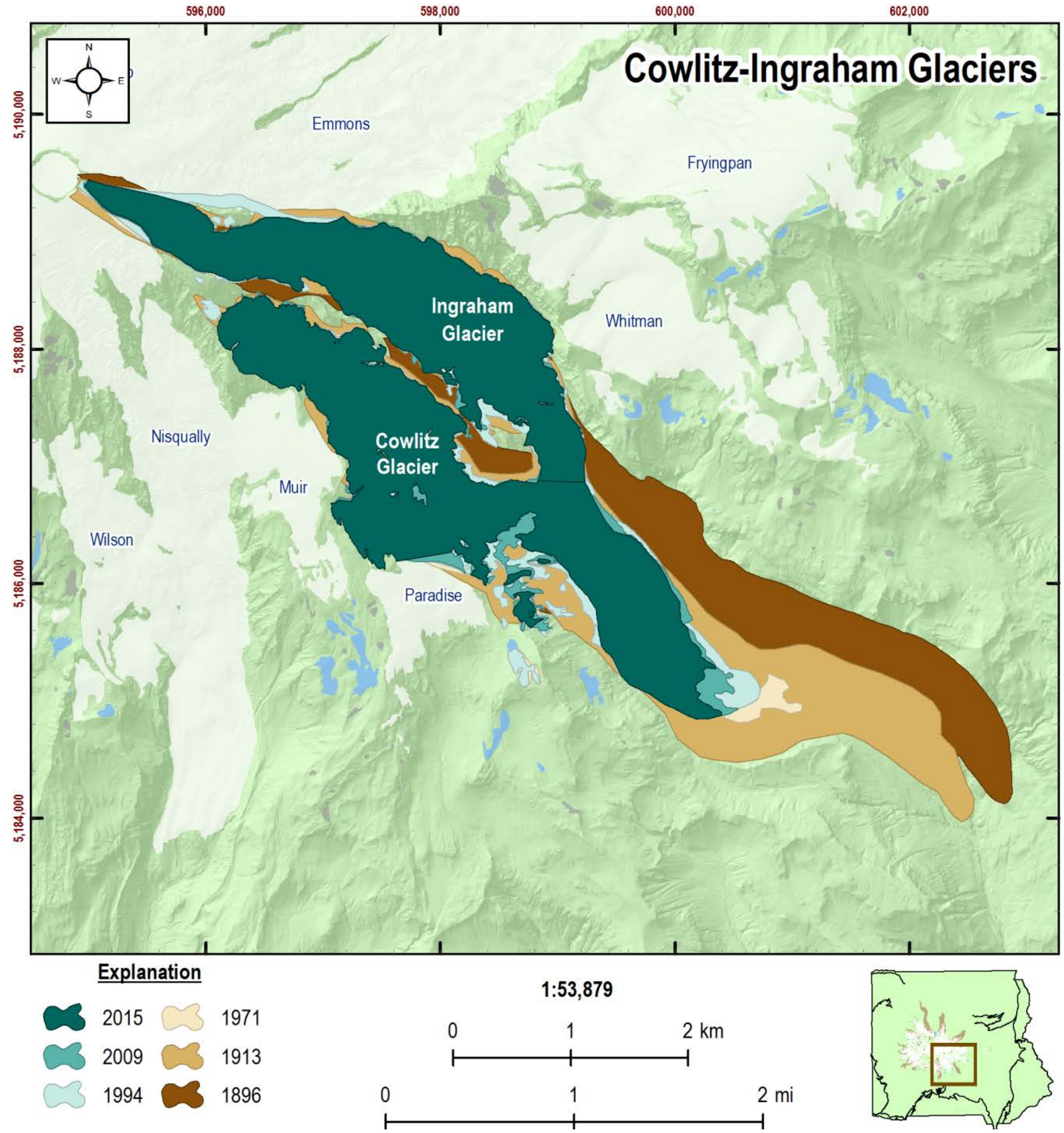
Carbon Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	8.29	8.46	8.01	7.98	7.45	7.26
Area, acres (ac)	2,049	2,089	1,980	1,971	1,842	1,793

	1913	1971	1994	2009	2015
1896	+0.17 km^2 (+2.0%)	-0.28 km^2 (-3.3%)	-0.31 km^2 (-3.8%)	-0.84 km^2 (-10.1%)	-1.03 km^2 (-12.5%)
1913	---	-0.44 km^2 (-5.2%)	-0.48 km^2 (-5.7%)	-1.00 km^2 (-11.8%)	-1.20 km^2 (-14.2%)
1971	---	---	-0.04 km^2 (-0.5%)	-0.56 km^2 (-7.0%)	-0.76 km^2 (-9.4%)
1994	---	---	---	-0.52 km^2 (-6.5%)	-0.72 km^2 (-9.0%)
2009	---	---	---	---	-0.20 km^2 (-2.7%)



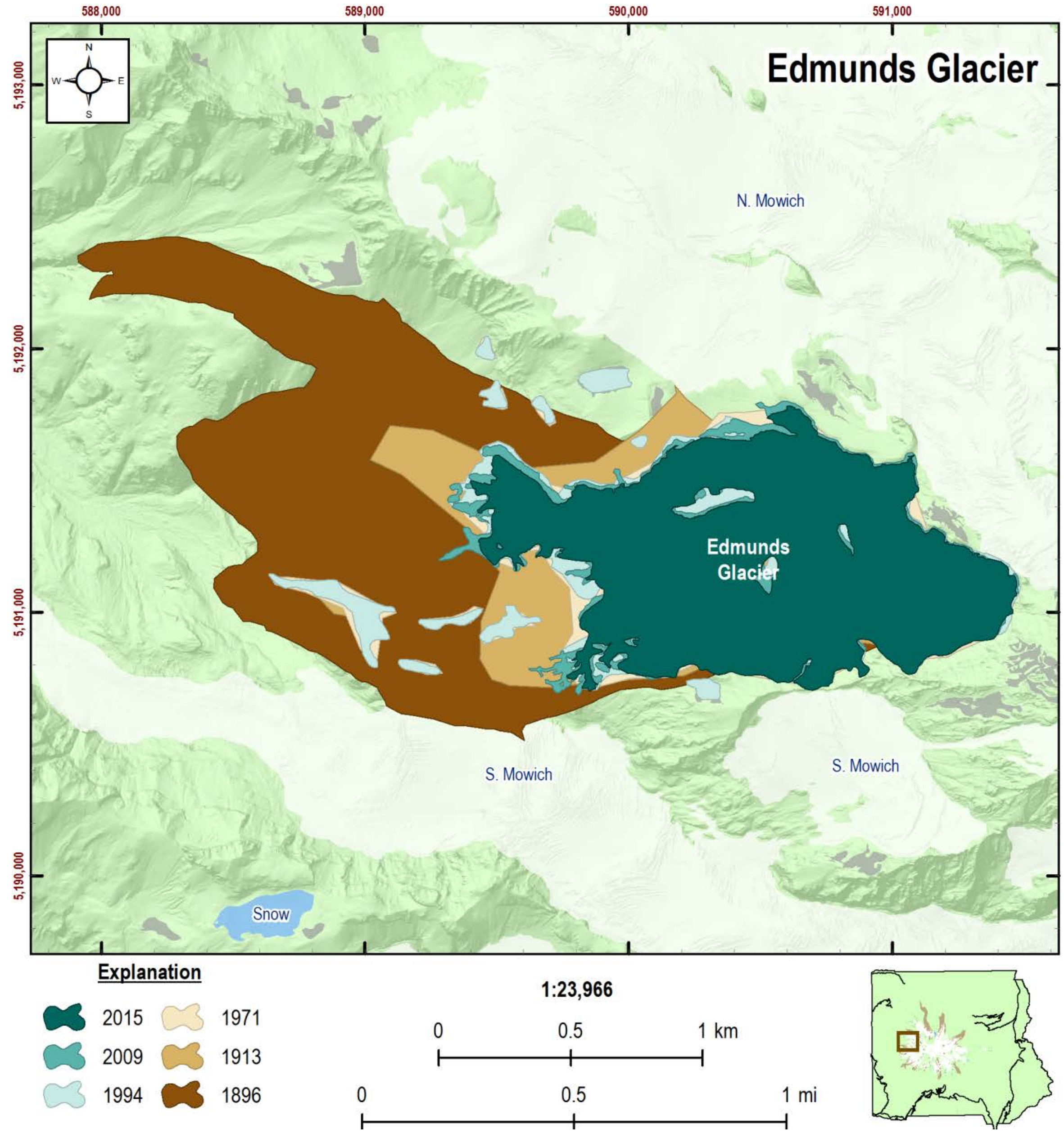
Columbia Crest Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km2)	0.32	0.11	0.25	0.20	0.12	0.18
Area, acres (ac)	80	26	62	49	29	45

	1913	1971	1994	2009	2015
1896	-0.21 km² (-66.8%)	-0.07 km² (-22.1%)	-0.12 km² (-38.6%)	-0.20 km² (-63.4%)	-0.14 km² (-43.9%)
1913	---	+0.14 km² (+134.6%)	+0.09 km² (+84.9%)	+0.01 km² (+10.4%)	+0.07 km² (+68.8%)
1971	---	---	-0.05 km² (-21.2%)	-0.13 km² (-53.0%)	-0.07 km² (-28.0%)
1994	---	---	---	-0.08 km² (-40.3%)	-0.02 km² (-8.7%)
2009	---	---	---	---	+0.06 km² (+53.0%)



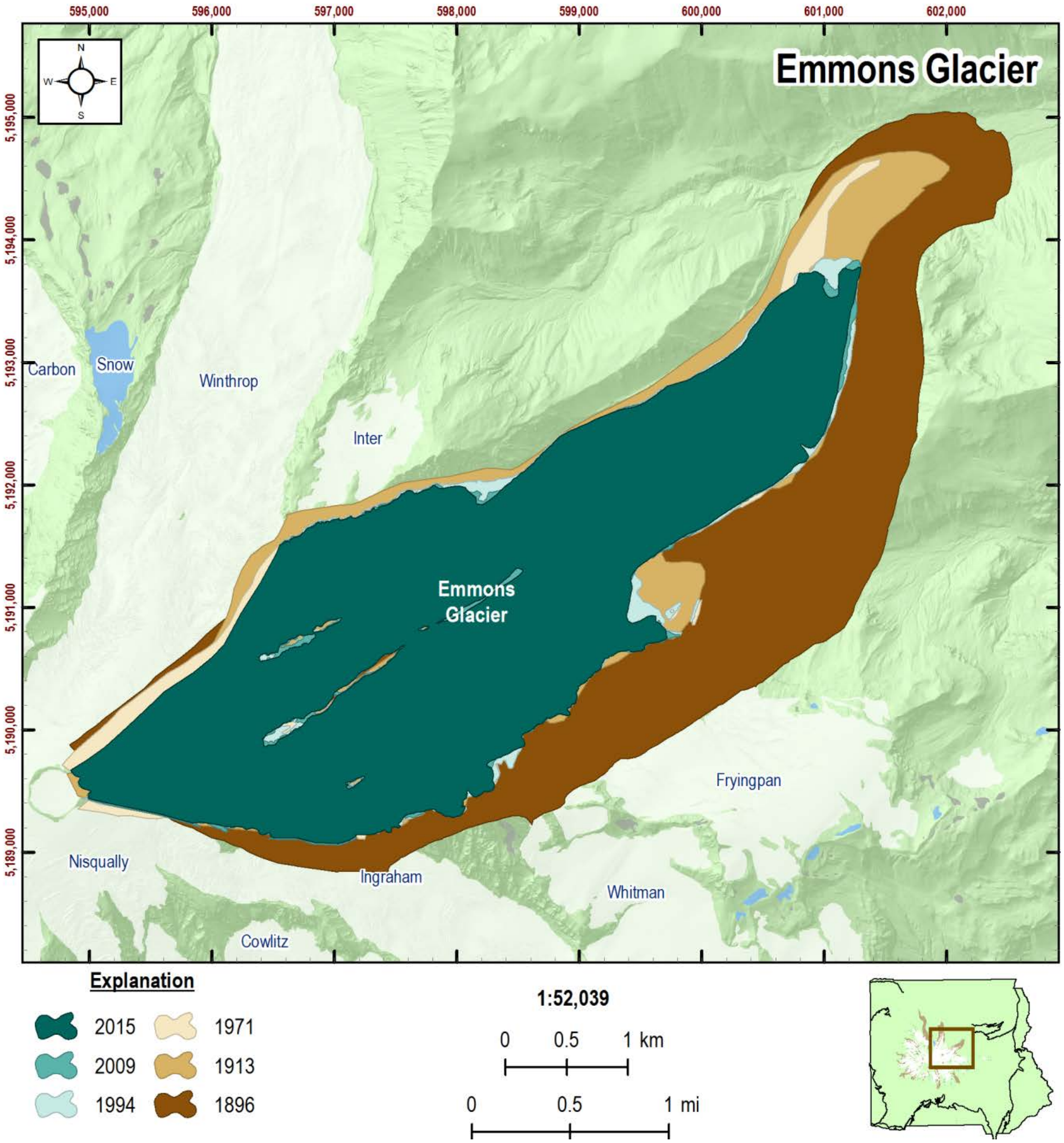
Cowlitz-Ingraham Glaciers	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	8.31	9.84	7.64	7.70	7.05	7.00
Area, acres (ac)	2,053	2,431	1,888	1,902	1,741	1,729

	1913	1971	1994	2009	2015
1896	+1.53 km^2 (+18.4%)	-0.67 km^2 (-8.1%)	-0.61 km^2 (-7.4%)	-1.26 km^2 (-15.2%)	-1.31 km^2 (-15.8%)
1913	---	-2.20 km^2 (-22.3%)	-2.14 km^2 (-21.8%)	-2.79 km^2 (-28.4%)	-2.84 km^2 (-28.9%)
1971	---	---	+0.06 km^2 (+0.8%)	-0.59 km^2 (-7.7%)	-0.64 km^2 (-8.4%)
1994	---	---	---	-0.65 km^2 (-8.4%)	-0.70 km^2 (-9.1%)
2009	---	---	---	---	-0.05 km^2 (-0.7%)



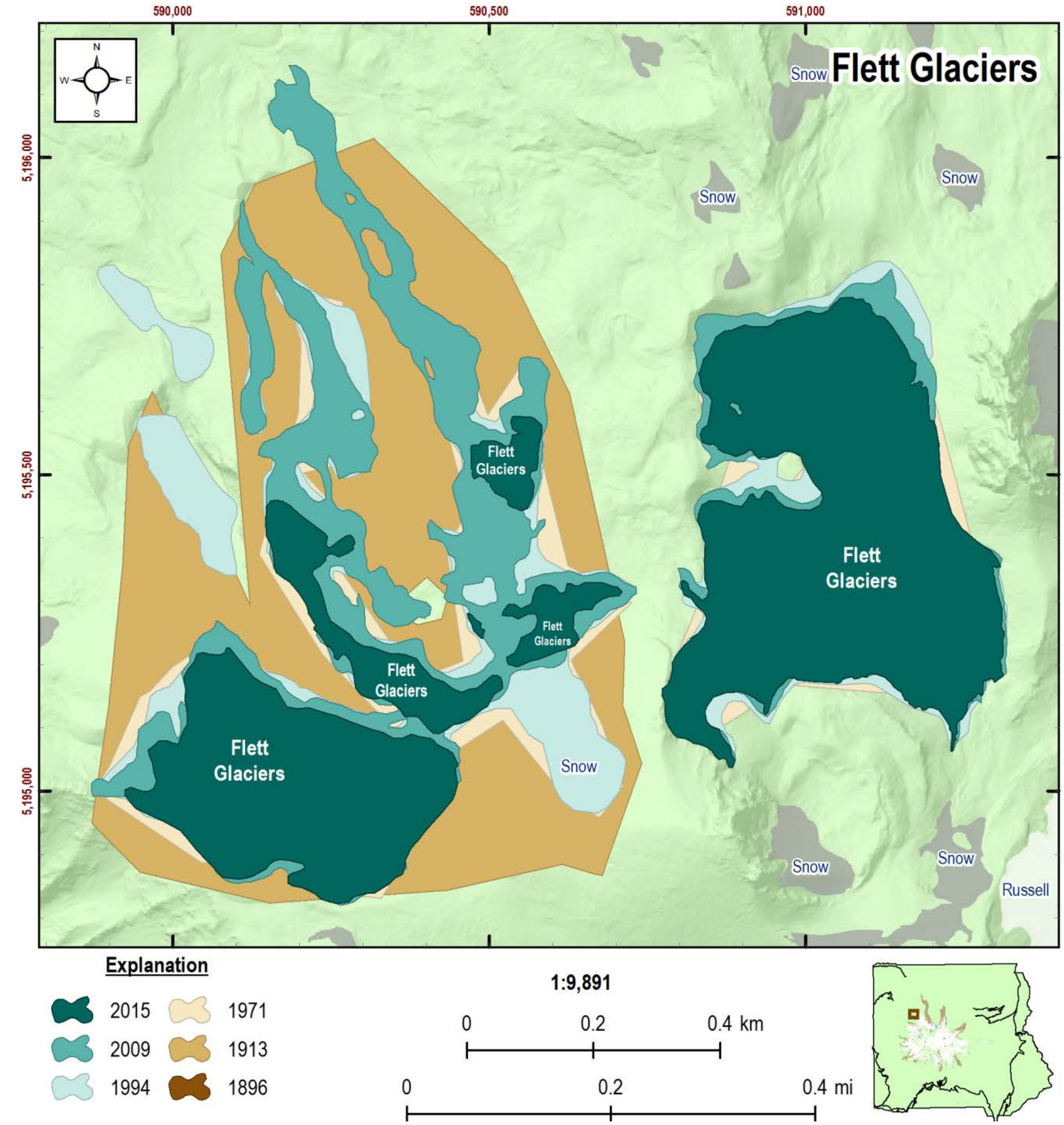
Edmunds Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	2.82	1.53	1.47	1.42	1.30	1.25
Area, acres (ac)	697	378	364	350	321	309

	1913	1971	1994	2009	2015
1896	-1.29 km² (-45.7%)	-1.35 km² (-47.7%)	-1.40 km² (-49.8%)	-1.52 km² (-53.9%)	-1.57 km² (-55.6%)
1913	---	-0.06 km² (-3.7%)	-0.11 km² (-7.4%)	-0.23 km² (-15.0%)	-0.28 km² (-18.1%)
1971	---	---	-0.06 km² (-3.9%)	-0.17 km² (-11.8%)	-0.22 km² (-15.0%)
1994	---	---	---	-0.12 km² (-8.2%)	-0.16 km² (-11.6%)
2009	---	---	---	---	-0.05 km² (-3.7%)



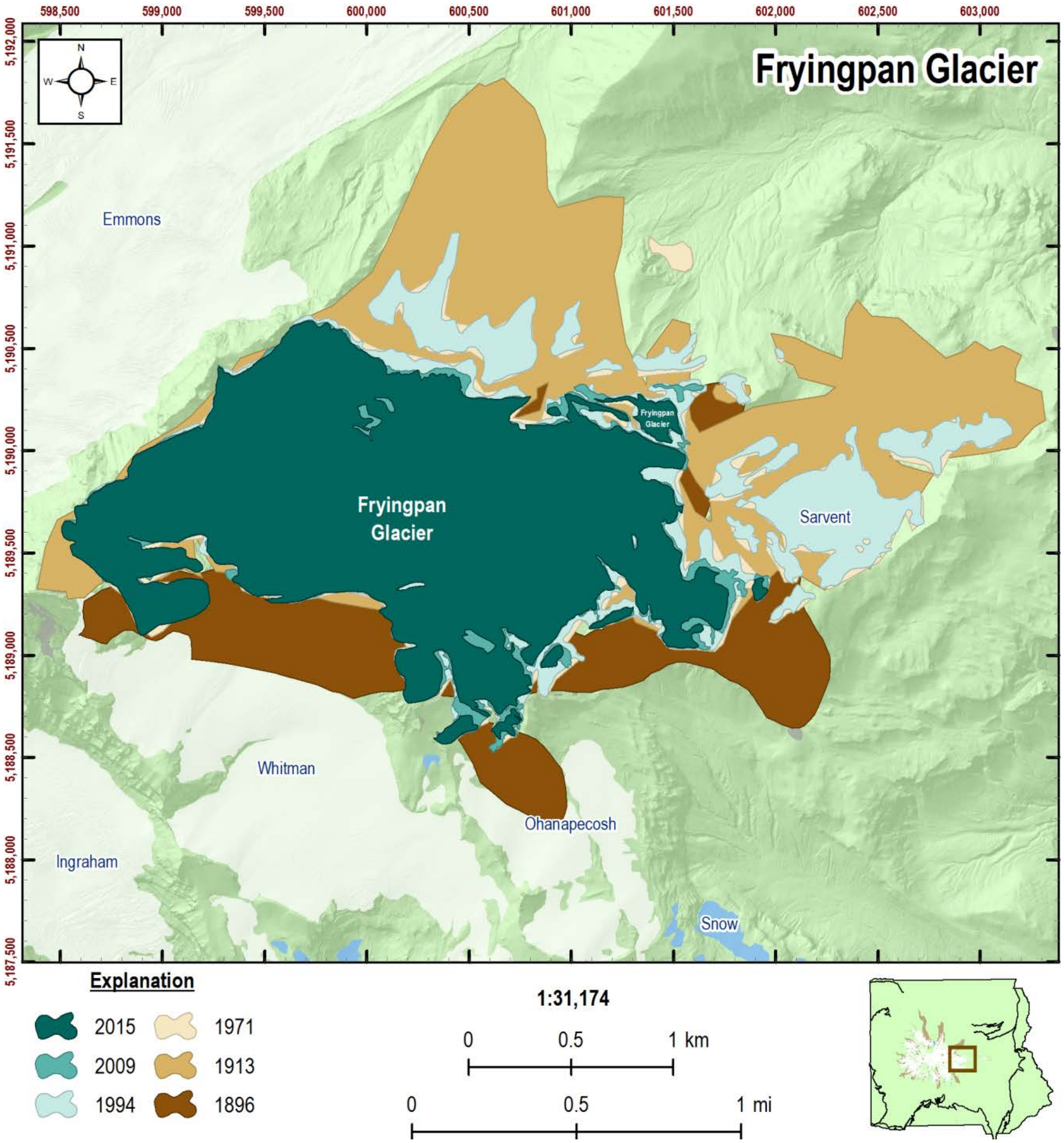
Emmons Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	17.46	12.62	11.16	11.22	10.98	11.03
Area, acres (ac)	4,314	3,119	2,757	2,773	2,713	2,725

	1913	1971	1994	2009	2015
1896	-4.84 km^2 (-27.7%)	-6.30 km^2 (-36.1%)	-6.24 km^2 (-35.7%)	-6.48 km^2 (-37.1%)	-6.43 km^2 (-36.8%)
1913	---	-1.46 km^2 (-11.6%)	-1.40 km^2 (-11.1%)	-1.64 km^2 (-13.0%)	-1.60 km^2 (-12.6%)
1971	---	---	+0.06 km^2 (+0.6%)	-0.18 km^2 (-1.6%)	-0.13 km^2 (-1.2%)
1994	---	---	---	-0.24 km^2 (-2.2%)	-0.20 km^2 (-1.7%)
2009	---	---	---	---	+0.05 km^2 (+0.4%)



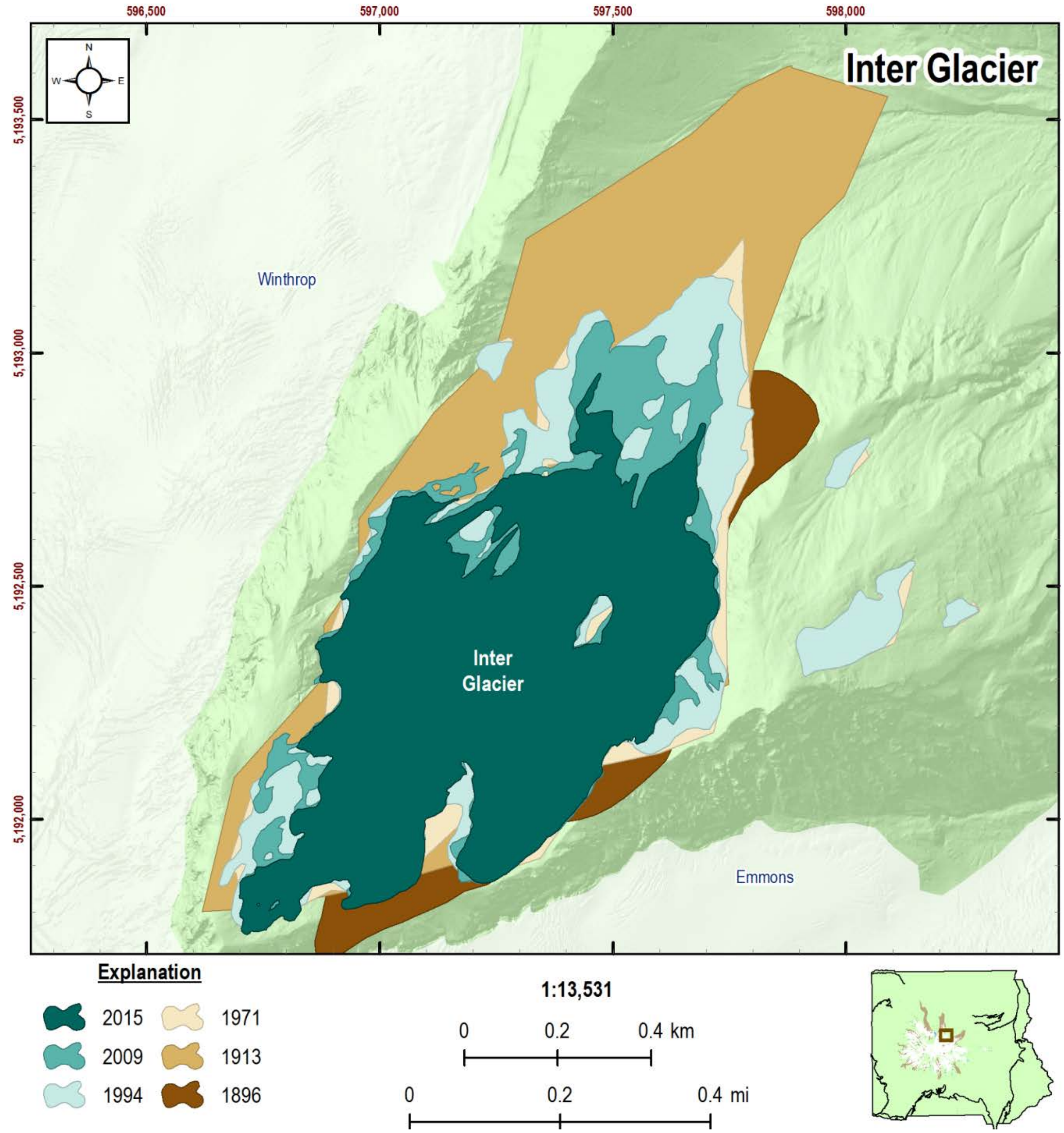
Flett Glaciers	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	---	0.74	0.58	0.62	0.58	0.41
Area, acres (ac)	---	182	142	152	144	100

	1913	1971	1994	2009	2015
1896	---	---	---	---	---
1913	---	-0.16 km^2 (-21.7%)	-0.12 km^2 (-16.5%)	-0.15 km^2 (-21.0%)	-0.33 km^2 (-44.9%)
1971	---	---	+0.04 km^2 (+6.8%)	+0.01 km^2 (+1.0%)	-0.17 km^2 (-29.6%)
1994	---	---	---	-0.03 km^2 (-5.4%)	-0.21 km^2 (-34.1%)
2009	---	---	---	---	-0.18 km^2 (-30.3%)



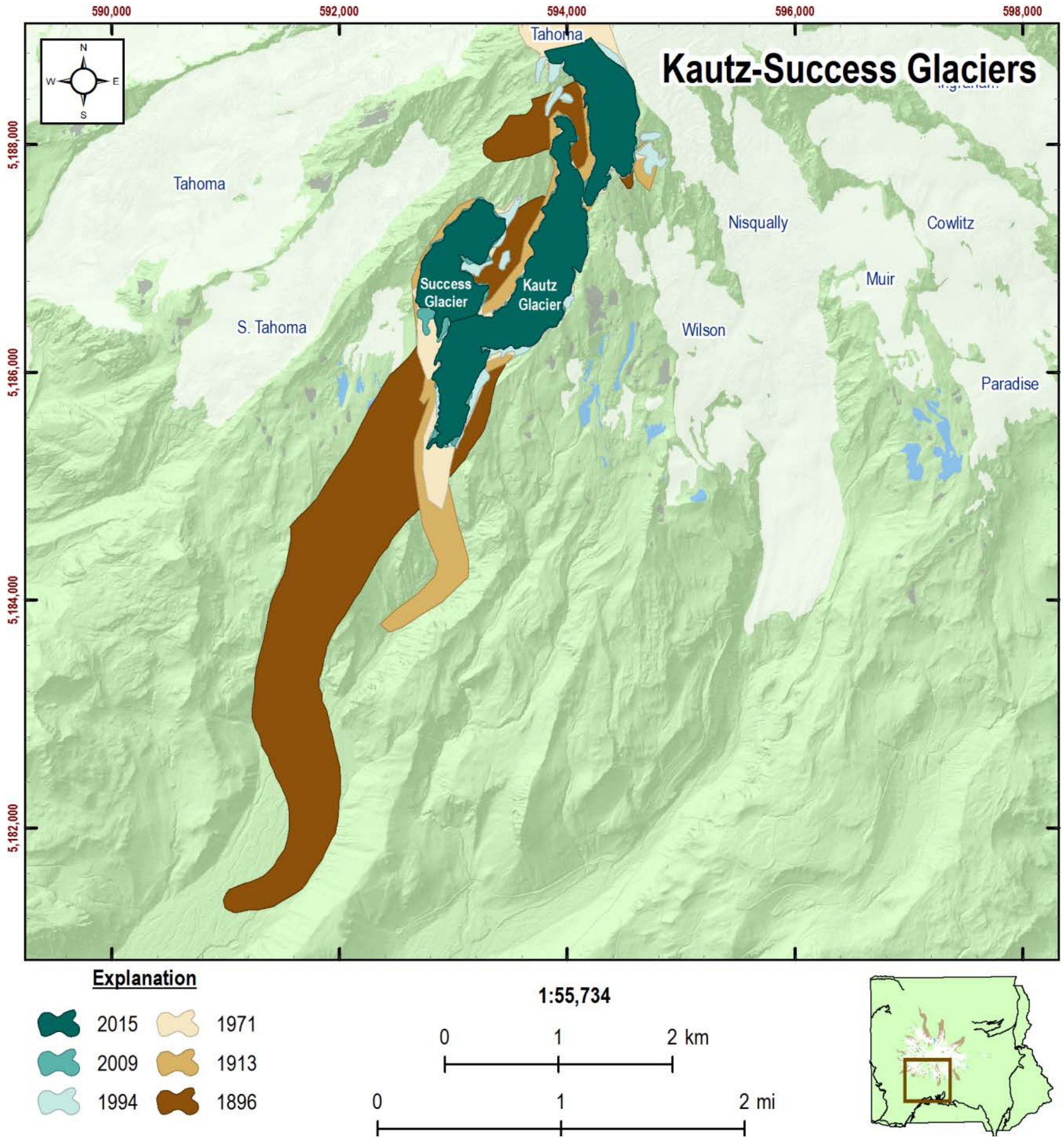
Fryingpan Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km2)	3.72	6.12	4.34	4.23	3.30	3.24
Area, acres (ac)	920	1,512	1,072	1,045	815	802

	1913	1971	1994	2009	2015
1896	+2.40 km² (+64.5%)	+0.62 km² (+16.6%)	+0.51 km² (+13.7%)	-0.43 km² (-11.4%)	-0.48 km² (-12.8%)
1913	---	-1.78 km² (-29.1%)	-1.89 km² (-30.9%)	-2.82 km² (-46.1%)	-2.88 km² (-47.0%)
1971	---	---	-0.11 km² (-2.5%)	-1.04 km² (-24.0%)	-1.09 km² (-25.2%)
1994	---	---	---	-0.93 km² (-22.1%)	-0.99 km² (-23.3%)
2009	---	---	---	---	-0.05 km² (-1.6%)



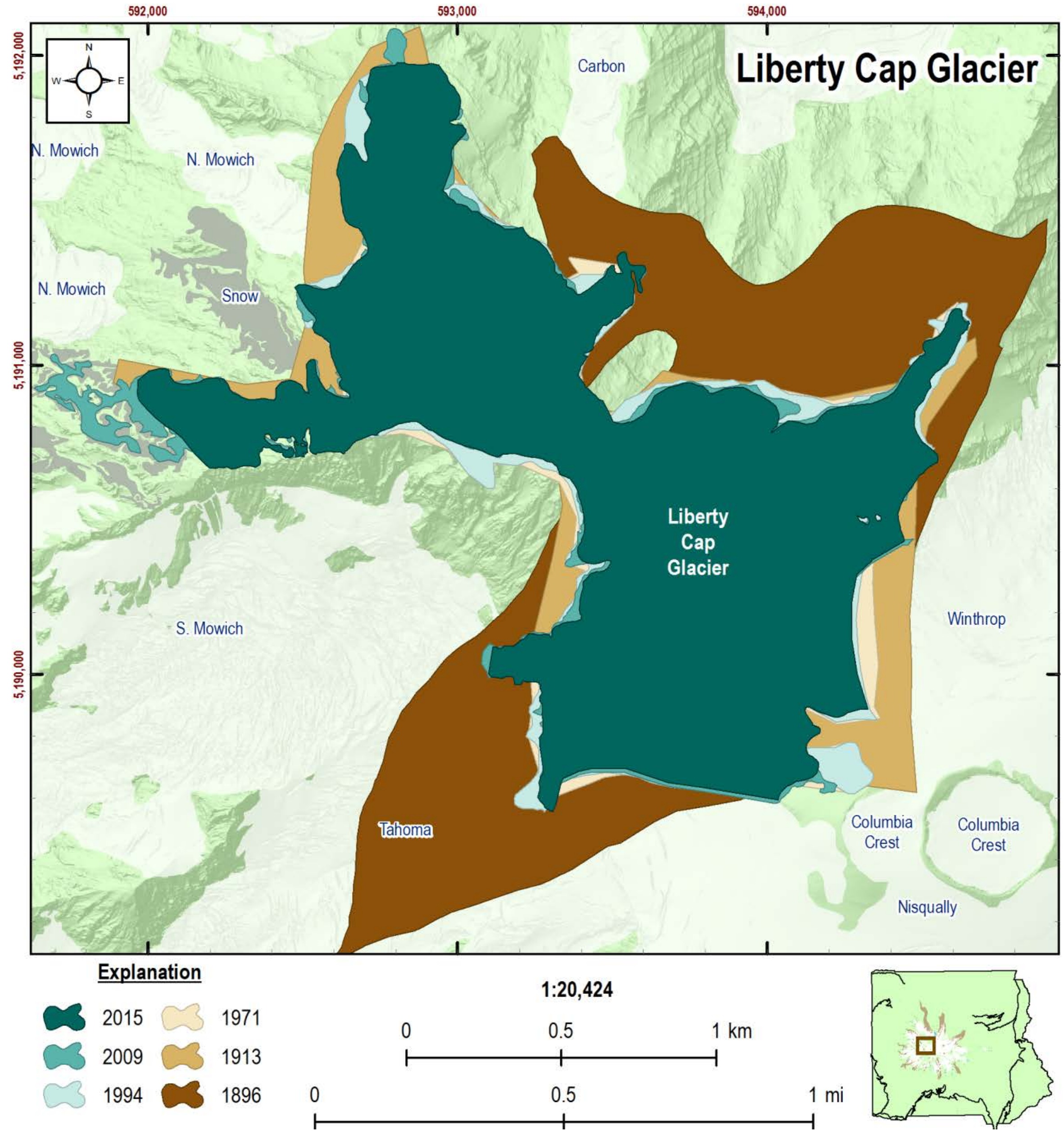
Inter Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km2)	0.57	1.14	0.84	0.83	0.67	0.57
Area, acres (ac)	141	283	207	204	164	142

	1913	1971	1994	2009	2015
1896	+0.57 km² (+100.5%)	+0.27 km² (+46.6%)	+0.26 km² (+44.8%)	+0.10 km² (+16.7%)	+0.00 km² (+0.7%)
1913	---	-0.31 km² (-26.9%)	-0.32 km² (-27.8%)	-0.48 km² (-41.8%)	-0.57 km² (-49.8%)
1971	---	---	-0.01 km² (-1.2%)	-0.17 km² (-20.4%)	-0.26 km² (-31.3%)
1994	---	---	---	-0.16 km² (-19.4%)	-0.25 km² (-30.5%)
2009	---	---	---	---	-0.09 km² (-13.7%)



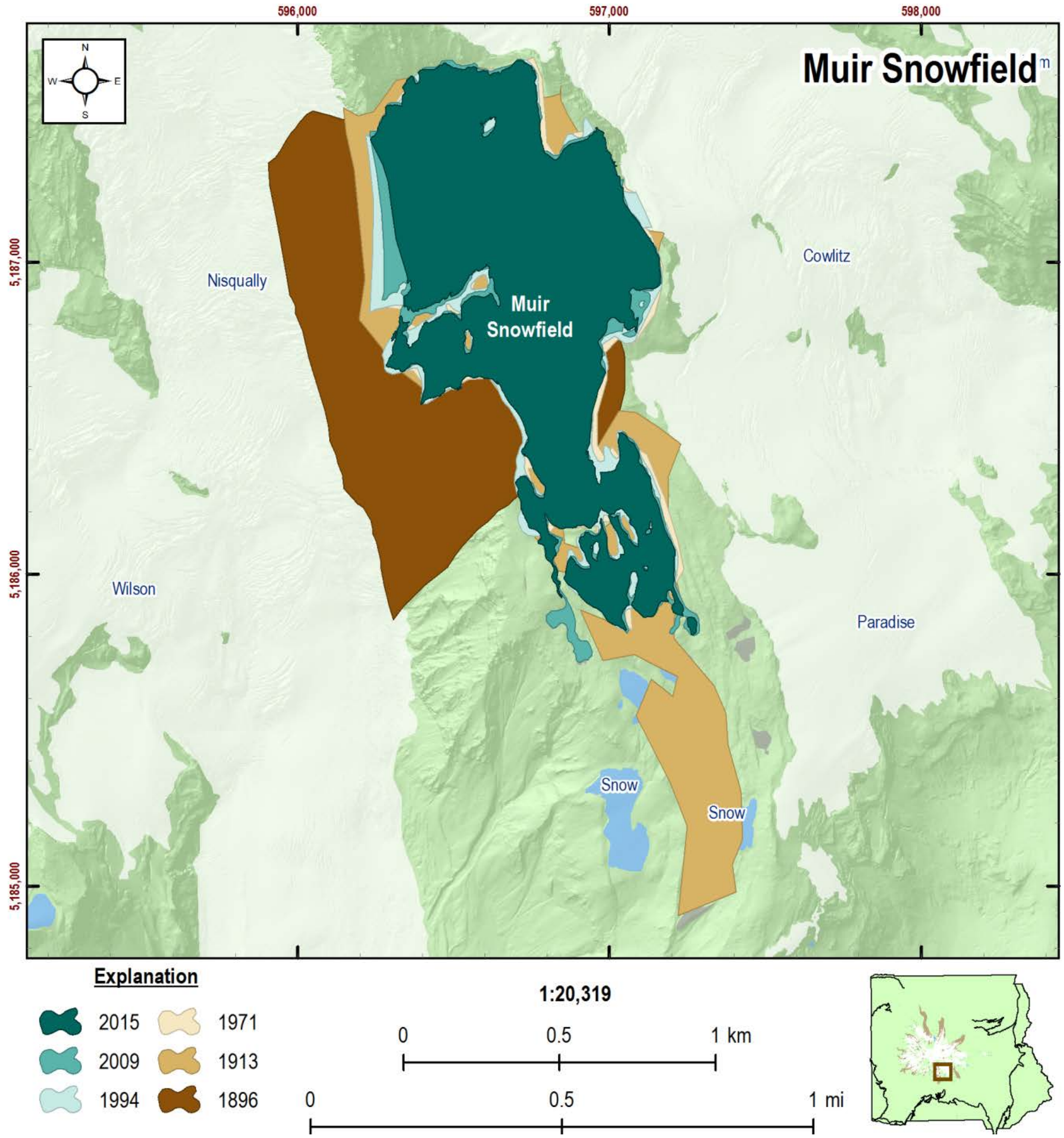
Kautz-Success Glaciers	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	5.17	3.03	2.73	2.20	2.13	2.08
Area, acres (ac)	1,279	748	674	544	525	514

	1913	1971	1994	2009	2015
1896	-2.15 km^2 (-41.5%)	-2.45 km^2 (-47.3%)	-2.97 km^2 (-57.5%)	-3.05 km^2 (-58.9%)	-3.09 km^2 (-59.8%)
1913	---	-0.30 km^2 (-9.9%)	-0.83 km^2 (-27.3%)	-0.90 km^2 (-29.8%)	-0.95 km^2 (-31.3%)
1971	---	---	-0.53 km^2 (-19.3%)	-0.60 km^2 (-22.1%)	-0.65 km^2 (-23.7%)
1994	---	---	---	-0.08 km^2 (-3.4%)	-0.12 km^2 (-5.5%)
2009	---	---	---	---	-0.04 km^2 (-2.1%)



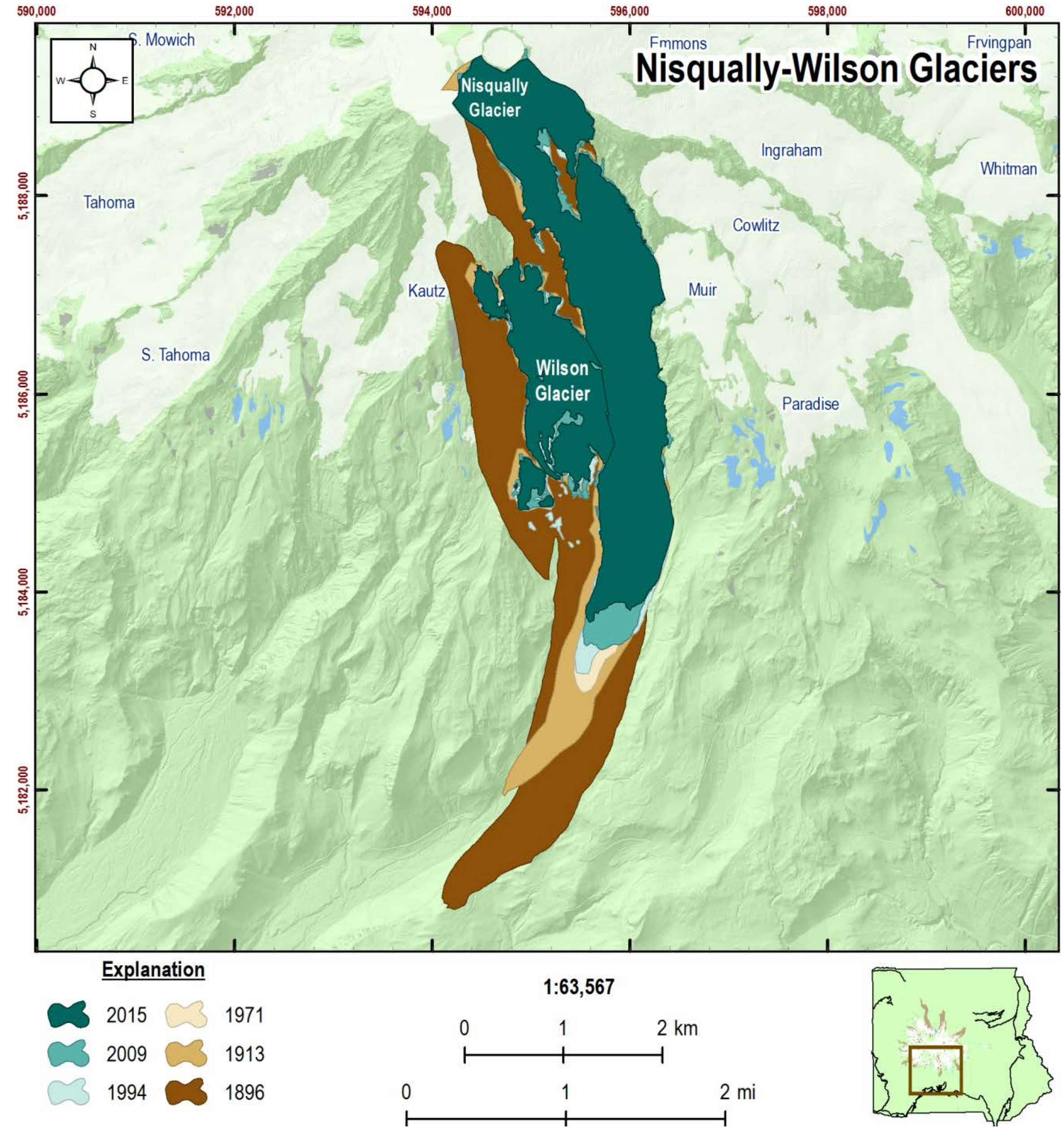
Liberty Cap Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	2.82	2.40	2.08	2.10	2.20	2.14
Area, acres (ac)	697	593	514	519	544	528

	1913	1971	1994	2009	2015
1896	-0.42 km^2 (-14.9%)	-0.74 km^2 (-26.3%)	-0.72 km^2 (-25.5%)	-0.62 km^2 (-22.1%)	-0.68 km^2 (-24.2%)
1913	---	-0.32 km^2 (-13.4%)	-0.30 km^2 (-12.4%)	-0.20 km^2 (-8.4%)	-0.26 km^2 (-10.9%)
1971	---	---	+0.02 km^2 (+1.1%)	+0.12 km^2 (+5.8%)	+0.06 km^2 (+2.9%)
1994	---	---	---	+0.10 km^2 (+4.7%)	+0.04 km^2 (+1.8%)
2009	---	---	---	---	-0.06 km^2 (-2.8%)



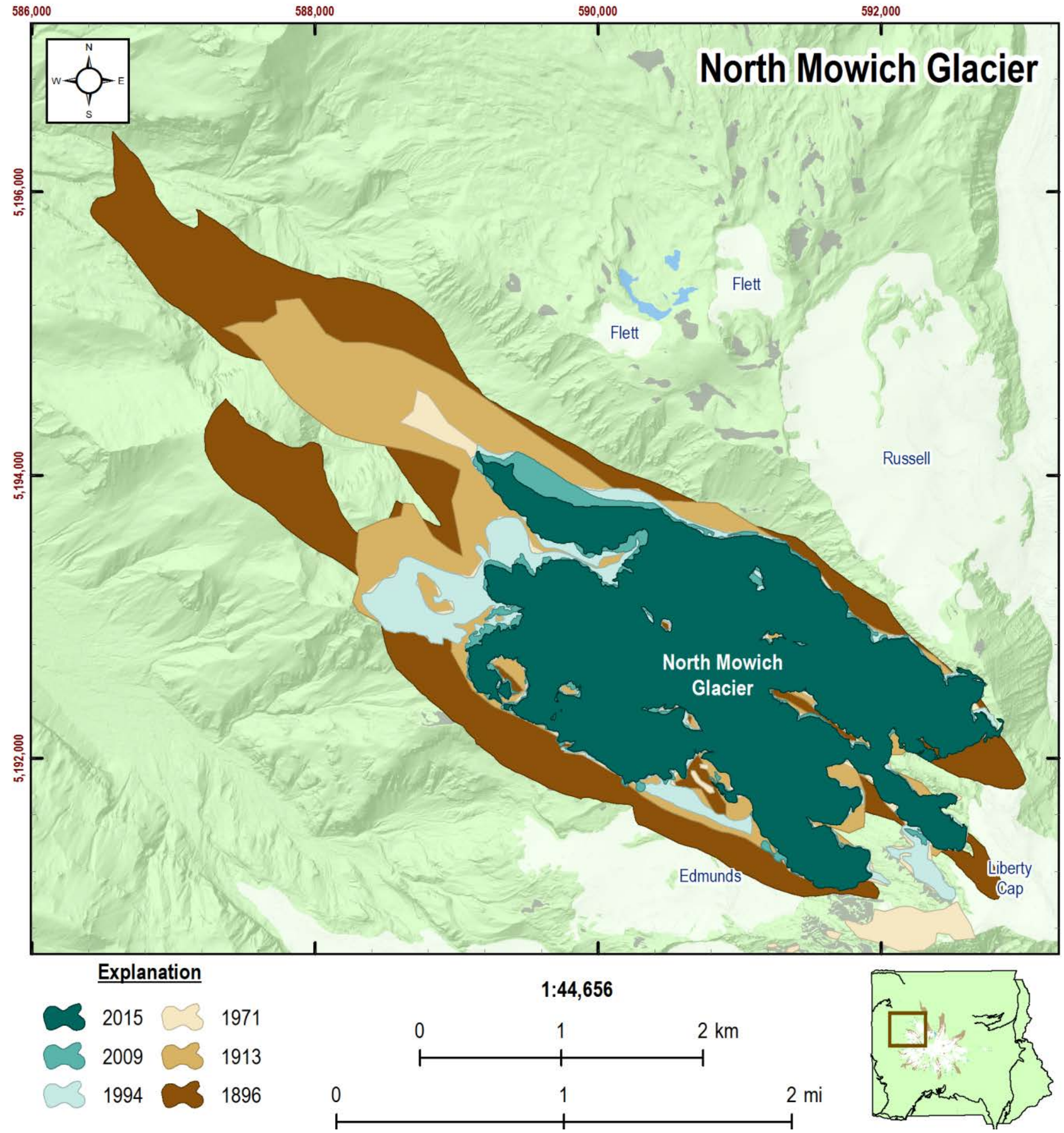
Muir Snowfield	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	1.13	1.22	0.97	0.98	0.92	0.88
Area, acres (ac)	280	300	239	241	227	216

	1913	1971	1994	2009	2015
1896	+0.08 km^2 (+7.4%)	-0.16 km^2 (-14.5%)	-0.16 km^2 (-13.7%)	-0.21 km^2 (-18.7%)	-0.26 km^2 (-22.7%)
1913	---	-0.25 km^2 (-20.4%)	-0.24 km^2 (-19.7%)	-0.30 km^2 (-24.3%)	-0.34 km^2 (-28.0%)
1971	---	---	+0.01 km^2 (+0.9%)	-0.05 km^2 (-5.0%)	-0.09 km^2 (-9.6%)
1994	---	---	---	-0.06 km^2 (-5.8%)	-0.10 km^2 (-10.4%)
2009	---	---	---	---	-0.04 km^2 (-4.9%)



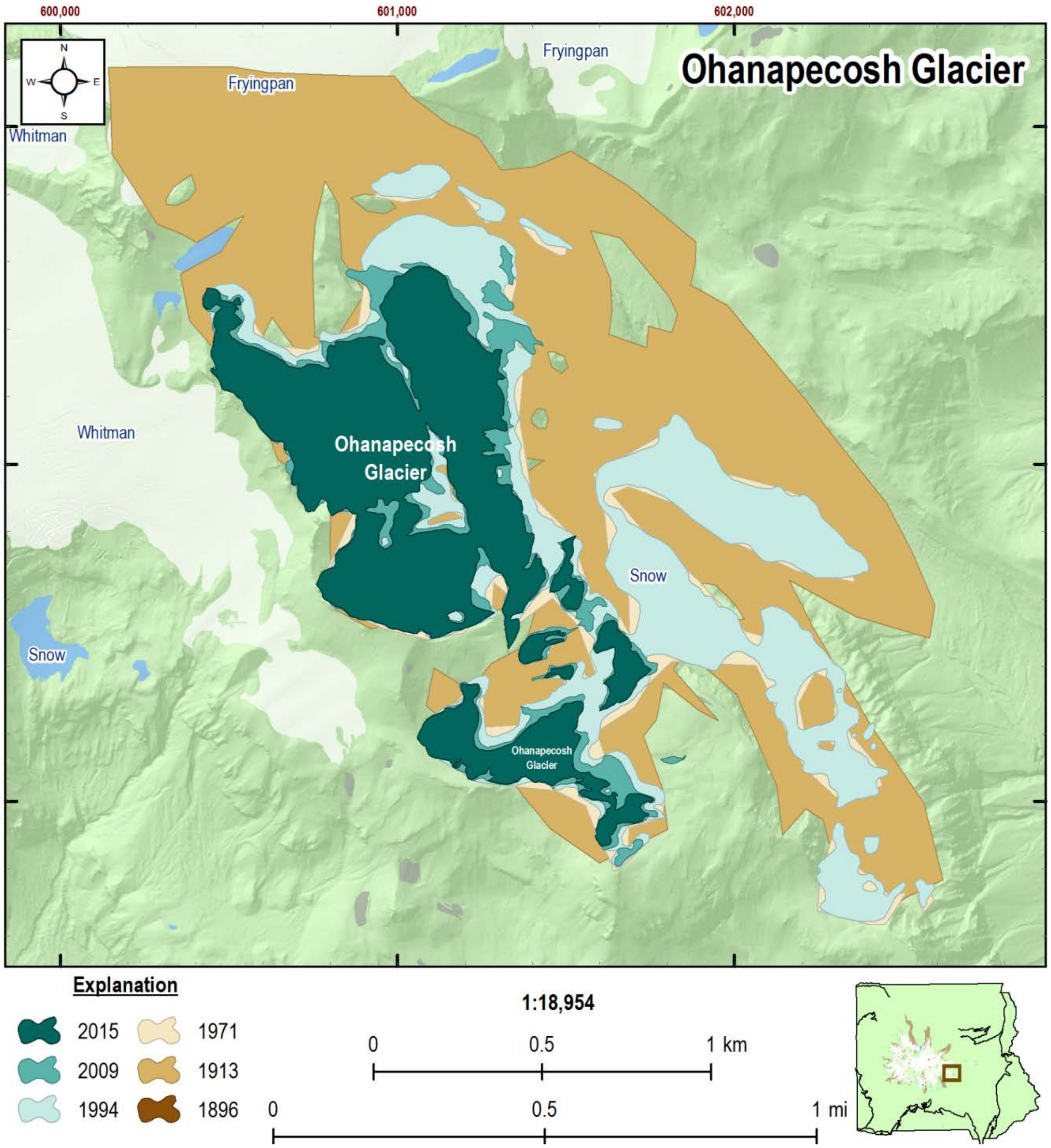
Nisqually-Wilson Glaciers	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	10.03	6.59	6.07	6.25	6.00	5.75
Area, acres (ac)	2,478	1,628	1,500	1,545	1,483	1,422

	1913	1971	1994	2009	2015
1896	-3.44 km² (-34.3%)	-3.95 km² (-39.4%)	-3.77 km² (-37.6%)	-4.02 km² (-40.1%)	-4.27 km² (-42.6%)
1913	---	-0.52 km² (-7.8%)	-0.33 km² (-5.1%)	-0.59 km² (-8.9%)	-0.83 km² (-12.7%)
1971	---	---	+0.18 km² (+3.0%)	-0.07 km² (-1.1%)	-0.32 km² (-5.2%)
1994	---	---	---	-0.25 km² (-4.0%)	-0.50 km² (-8.0%)
2009	---	---	---	---	-0.25 km² (-4.2%)



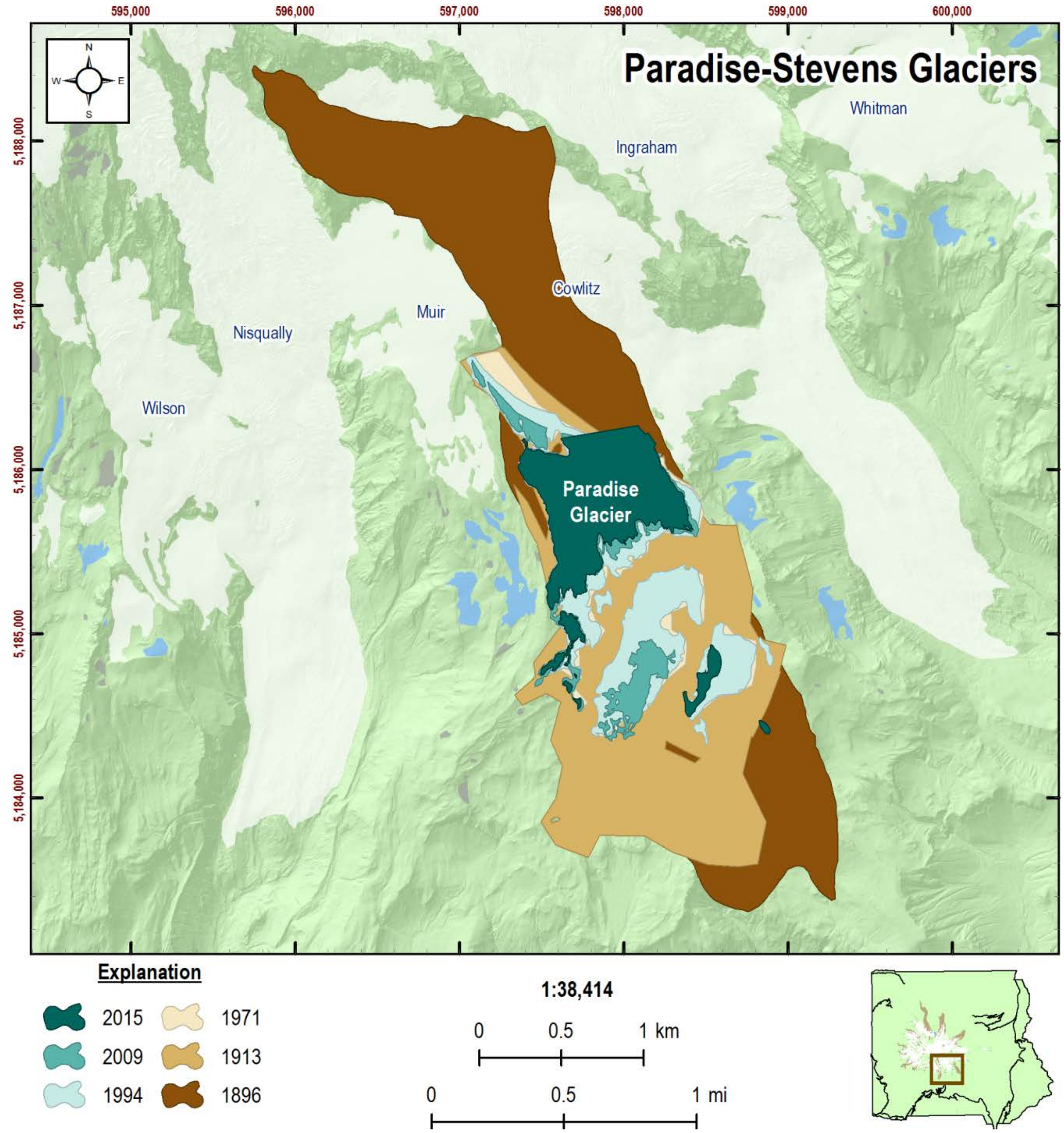
North Mowich Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	11.07	8.03	6.26	6.11	5.21	5.14
Area, acres (ac)	2,736	1,985	1,547	1,509	1,287	1,271

	1913	1971	1994	2009	2015
1896	-3.04 km^2 (-27.5%)	-4.81 km^2 (-43.5%)	-4.97 km^2 (-44.8%)	-5.87 km^2 (-53.0%)	-5.93 km^2 (-53.5%)
1913	---	-1.77 km^2 (-22.1%)	-1.92 km^2 (-24.0%)	-2.83 km^2 (-35.2%)	-2.89 km^2 (-36.0%)
1971	---	---	-0.15 km^2 (-2.4%)	-1.05 km^2 (-16.8%)	-1.12 km^2 (-17.8%)
1994	---	---	---	-0.90 km^2 (-14.8%)	-0.96 km^2 (-15.8%)
2009	---	---	---	---	-0.06 km^2 (-1.2%)



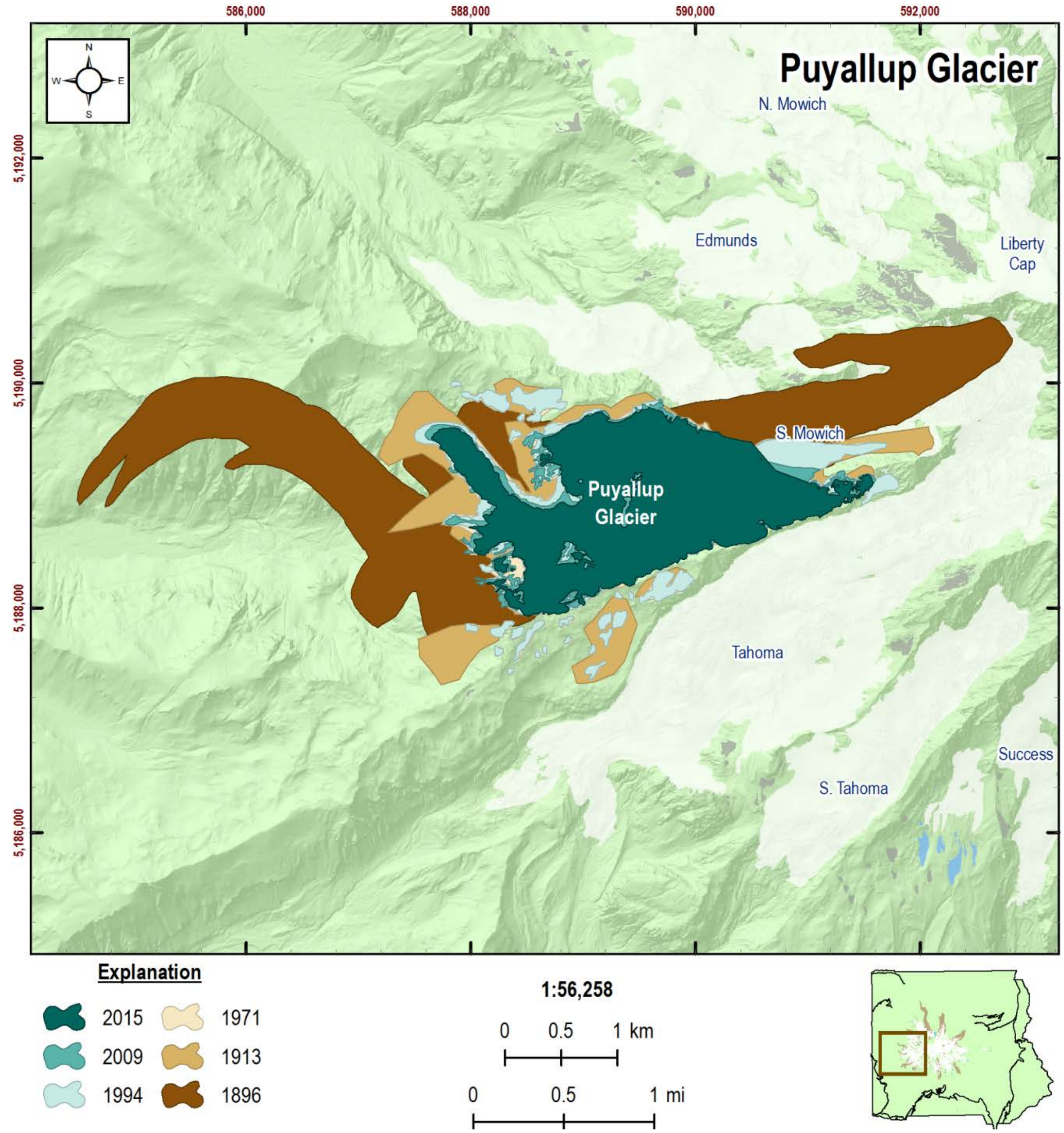
Ohanapecosh Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	---	2.97	1.37	1.39	0.79	0.67
Area, acres (ac)	---	733	338	343	194	165

	1913	1971	1994	2009	2015
1896	---	---	---	---	---
1913	---	-1.60 km^2 (-53.9%)	-1.58 km^2 (-53.2%)	-2.18 km^2 (-73.5%)	-2.30 km^2 (-77.5%)
1971	---	---	+0.02 km^2 (+1.4%)	-0.58 km^2 (-42.6%)	-0.70 km^2 (-51.2%)
1994	---	---	---	-0.60 km^2 (-43.4%)	-0.72 km^2 (-51.8%)
2009	---	---	---	---	-0.12 km^2 (-14.8%)



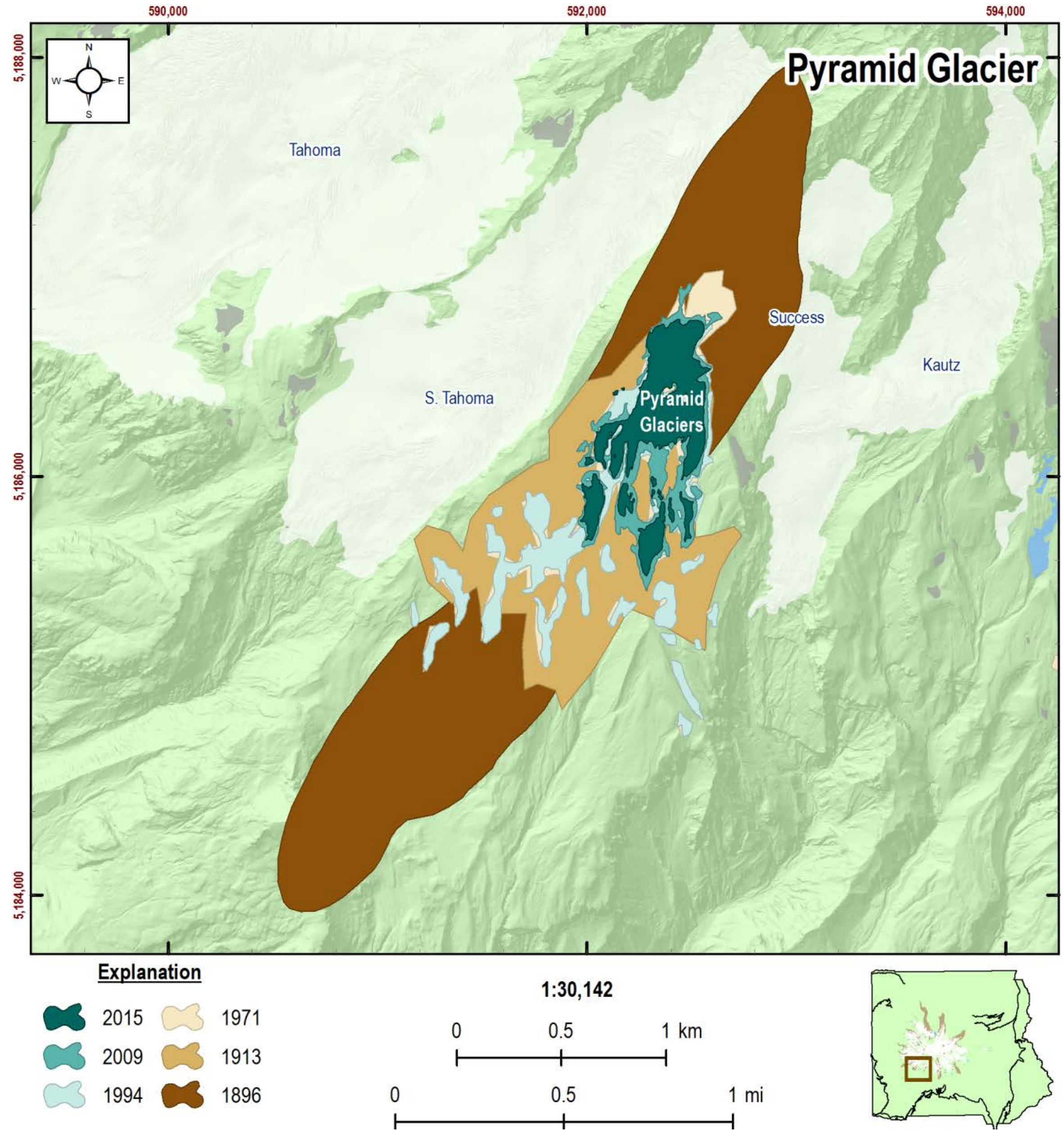
Paradise-Stevens Glaciers	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	4.86	3.19	1.36	1.34	0.78	0.64
Area, acres (ac)	1,202	787	337	331	192	159

	1913	1971	1994	2009	2015
1896	-1.68 km^2 (-34.5%)	-3.50 km^2 (-72.0%)	-3.53 km^2 (-72.5%)	-4.09 km^2 (-84.0%)	-4.22 km^2 (-86.7%)
1913	---	-1.82 km^2 (-57.2%)	-1.85 km^2 (-58.0%)	-2.41 km^2 (-75.6%)	-2.54 km^2 (-79.8%)
1971	---	---	-0.03 km^2 (-1.9%)	-0.59 km^2 (-43.0%)	-0.72 km^2 (-52.7%)
1994	---	---	---	-0.56 km^2 (-41.9%)	-0.69 km^2 (-51.8%)
2009	---	---	---	---	-0.13 km^2 (-17.1%)



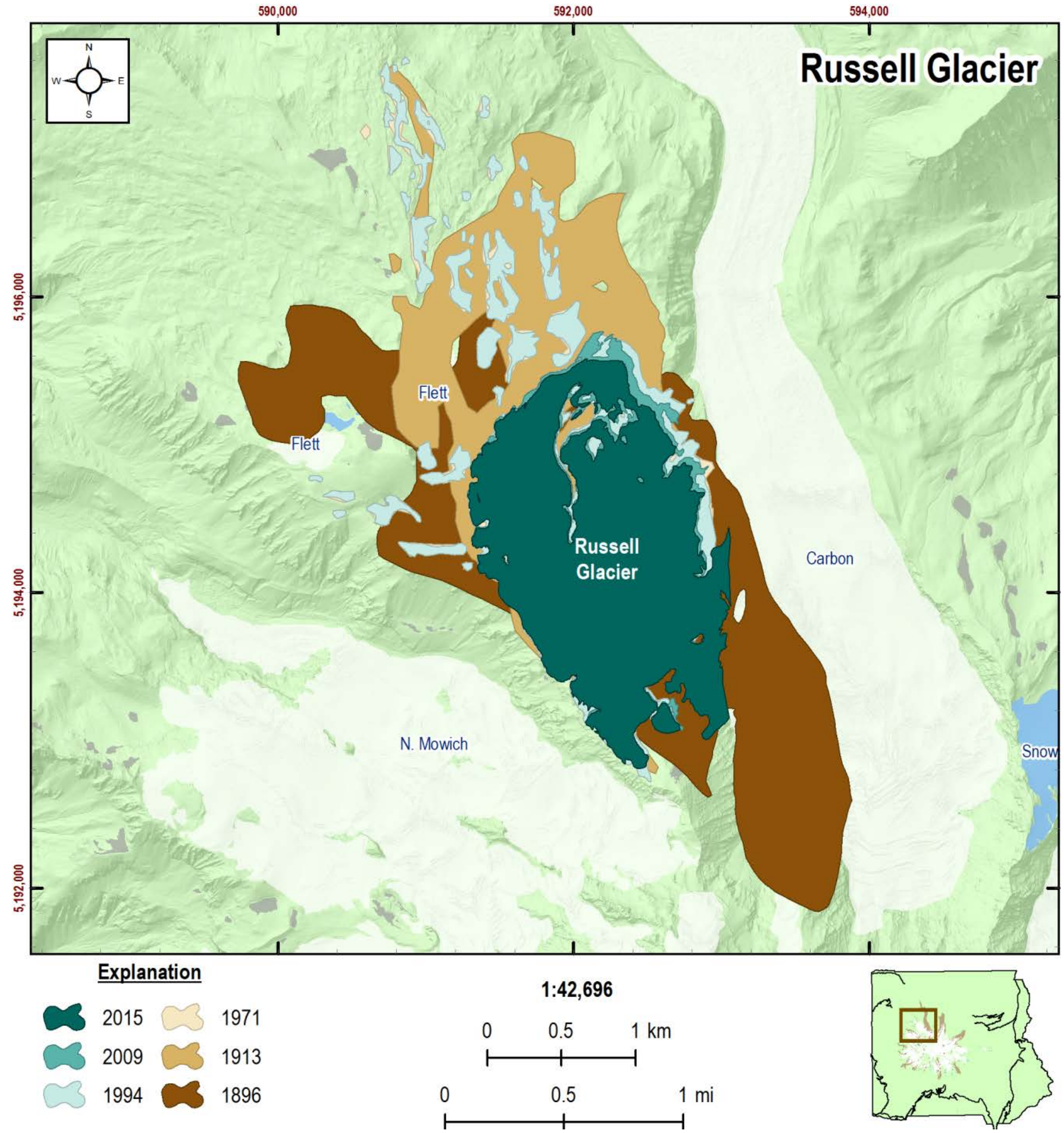
Puyallup Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	8.46	5.21	4.32	4.35	3.52	3.26
Area, acres (ac)	2,091	1,288	1,067	1,074	870	805

	1913	1971	1994	2009	2015
1896	-3.25 km^2 (-38.4%)	-4.15 km^2 (-49.0%)	-4.12 km^2 (-48.6%)	-4.94 km^2 (-58.4%)	-5.21 km^2 (-61.5%)
1913	---	-0.90 km^2 (-17.2%)	-0.86 km^2 (-16.6%)	-1.69 km^2 (-32.5%)	-1.95 km^2 (-37.5%)
1971	---	---	+0.03 km^2 (+0.7%)	-0.80 km^2 (-18.5%)	-1.06 km^2 (-24.5%)
1994	---	---	---	-0.83 km^2 (-19.1%)	-1.09 km^2 (-25.1%)
2009	---	---	---	---	-0.26 km^2 (-7.4%)



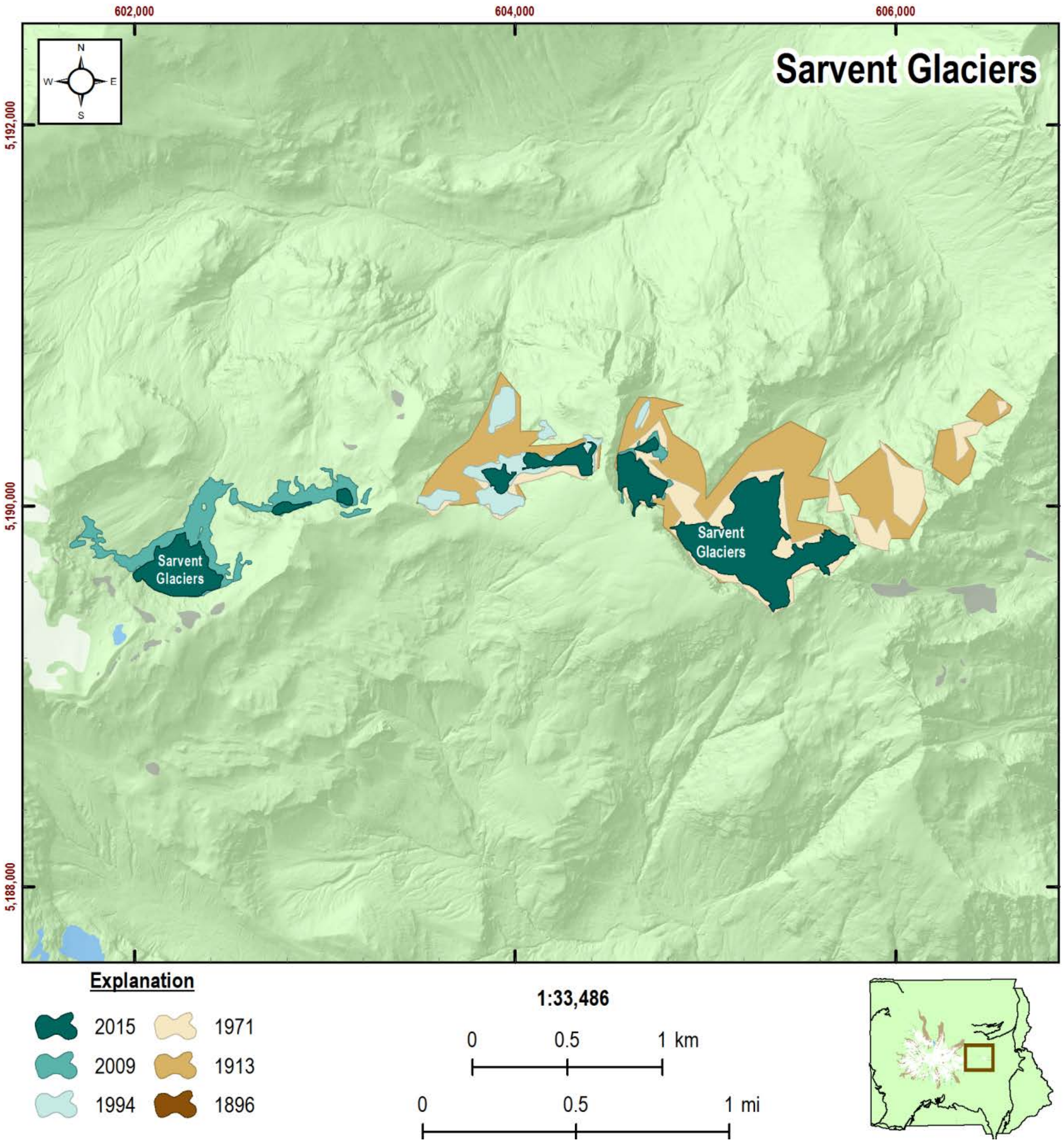
Pyramid Glaciers	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	2.75	1.39	0.71	0.64	0.38	0.26
Area, acres (ac)	679	344	175	159	94	65

	1913	1971	1994	2009	2015
1896	-1.35 km^2 (-49.2%)	-2.04 km^2 (-74.2%)	-2.10 km^2 (-76.5%)	-2.37 km^2 (-86.2%)	-2.48 km^2 (-90.5%)
1913	---	-0.68 km^2 (-49.1%)	-0.75 km^2 (-53.7%)	-1.02 km^2 (-72.8%)	-1.13 km^2 (-81.2%)
1971	---	---	-0.06 km^2 (-9.1%)	-0.33 km^2 (-46.6%)	-0.45 km^2 (-63.0%)
1994	---	---	---	-0.27 km^2 (-41.3%)	-0.38 km^2 (-59.3%)
2009	---	---	---	---	-0.12 km^2 (-30.7%)



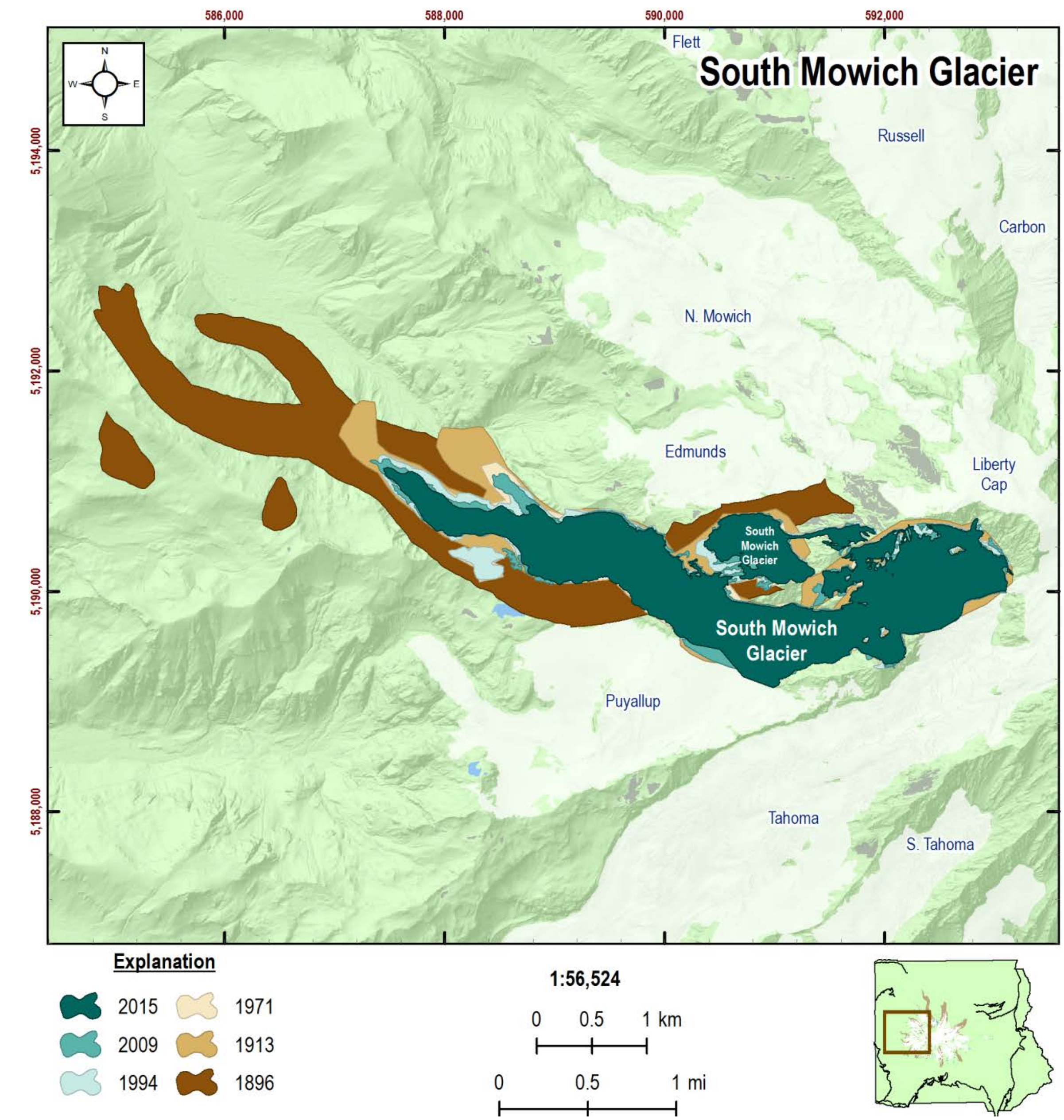
Russell Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	6.61	4.91	3.57	3.64	2.79	2.89
Area, acres (ac)	1,632	1,213	883	899	689	715

	1913	1971	1994	2009	2015
1896	-1.70 km^2 (-25.7%)	-3.03 km^2 (-45.9%)	-2.97 km^2 (-44.9%)	-3.82 km^2 (-57.8%)	-3.71 km^2 (-56.2%)
1913	---	-1.33 km^2 (-27.2%)	-1.27 km^2 (-25.9%)	-2.12 km^2 (-43.2%)	-2.02 km^2 (-41.1%)
1971	---	---	+0.06 km^2 (+1.8%)	-0.78 km^2 (-22.0%)	-0.68 km^2 (-19.1%)
1994	---	---	---	-0.85 km^2 (-23.3%)	-0.74 km^2 (-20.5%)
2009	---	---	---	---	+0.10 km^2 (+3.7%)



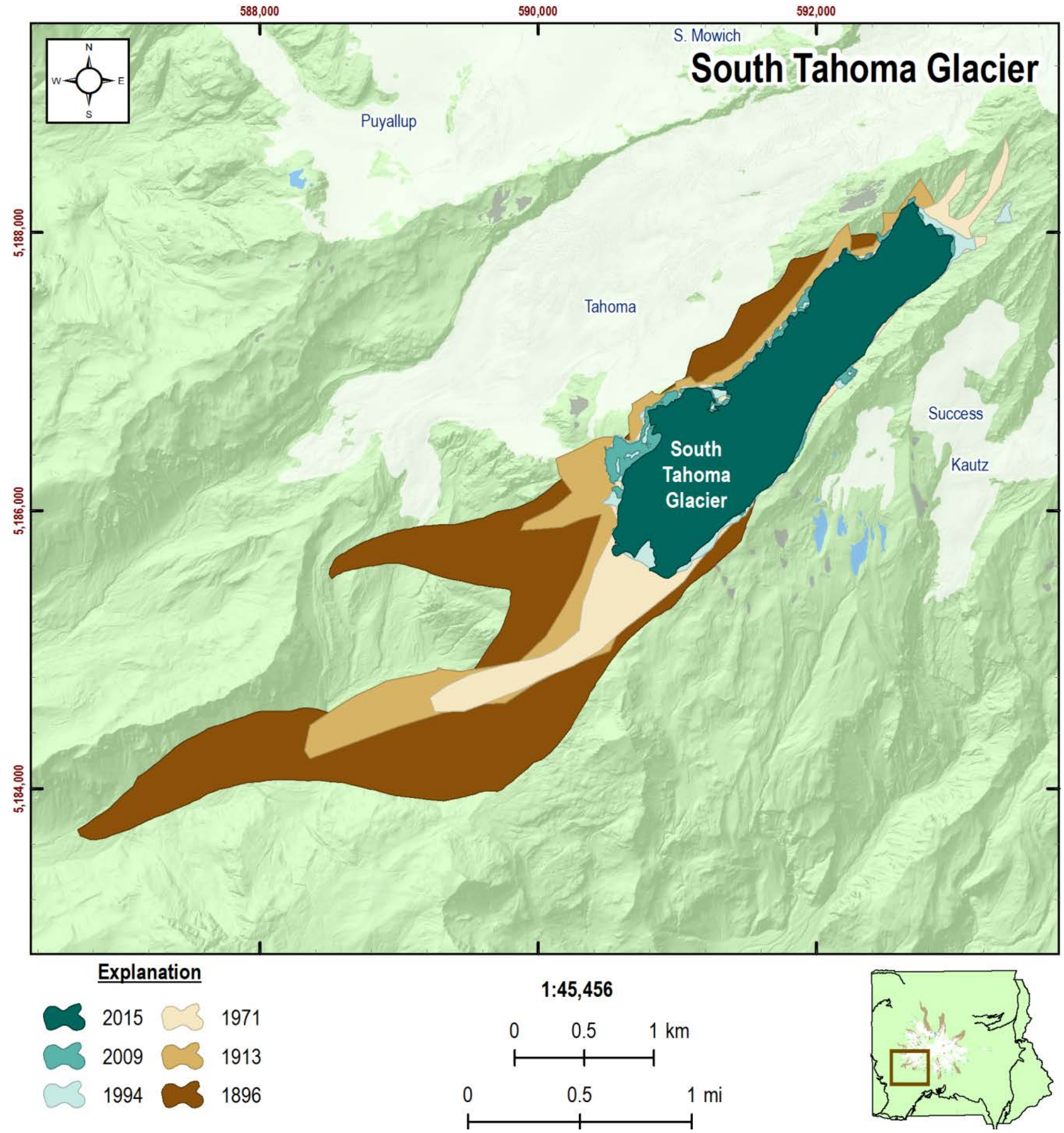
Sarvent Glaciers	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	---	1.15	0.69	0.15	0.69	0.45
Area, acres (ac)	---	284	170	36	172	112

	1913	1971	1994	2009	2015
1896	---	---	---	---	---
1913	---	-0.46 km^2 (-40.2%)	-1.00 km^2 (-87.3%)	-0.45 km^2 (-39.4%)	-0.69 km^2 (-60.4%)
1971	---	---	-0.54 km^2 (-78.8%)	+0.01 km^2 (+1.3%)	-0.23 km^2 (-33.7%)
1994	---	---	---	+0.55 km^2 (+377.0%)	+0.31 km^2 (+212.1%)
2009	---	---	---	---	-0.24 km^2 (-34.6%)



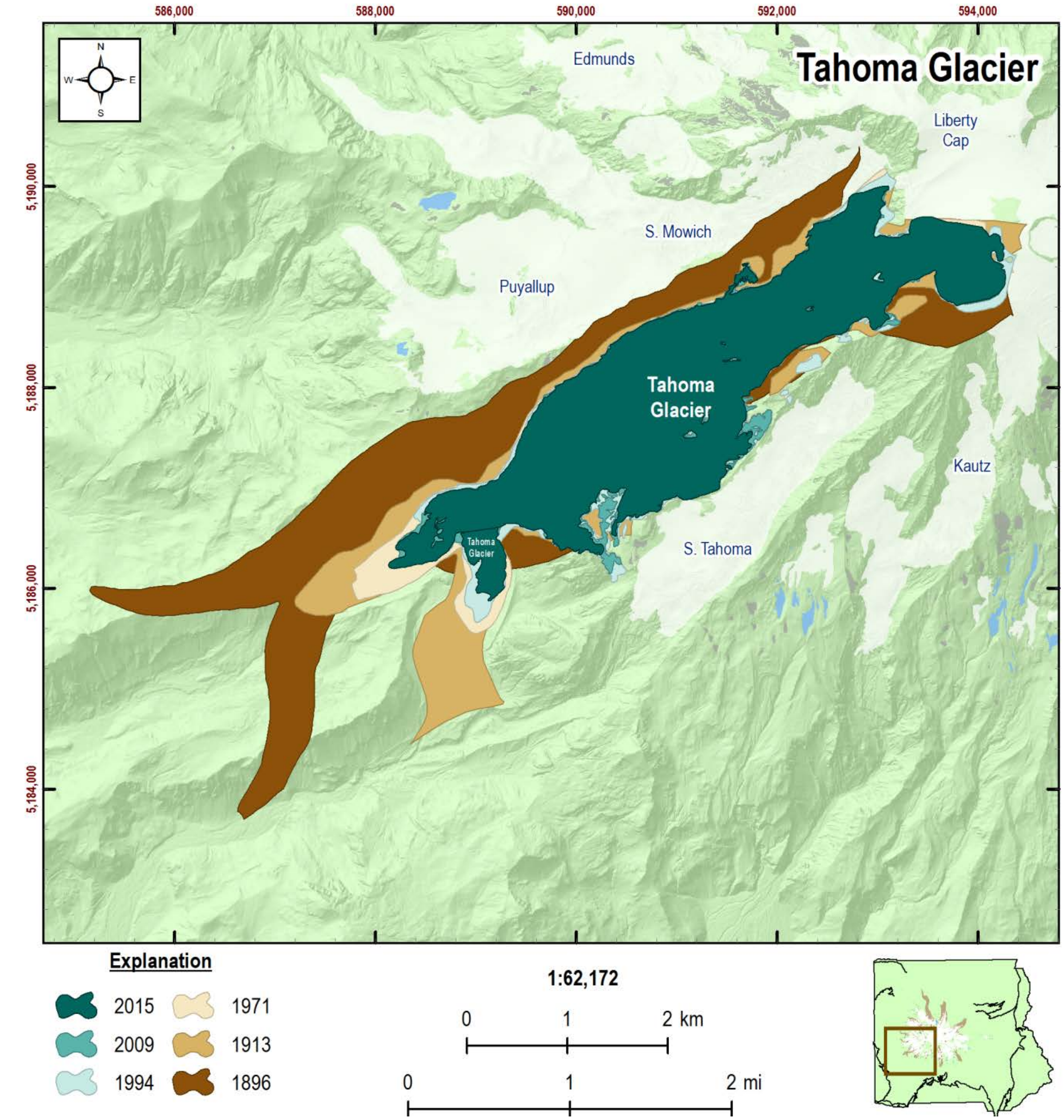
South Mowich Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	5.33	4.70	4.09	4.06	3.96	3.77
Area, acres (ac)	1,317	1,161	1,011	1,003	979	930

	1913	1971	1994	2009	2015
1896	-0.63 km^2 (-11.8%)	-1.24 km^2 (-23.3%)	-1.27 km^2 (-23.8%)	-1.37 km^2 (-25.7%)	-1.57 km^2 (-29.4%)
1913	---	-0.61 km^2 (-13.0%)	-0.64 km^2 (-13.6%)	-0.74 km^2 (-15.7%)	-0.93 km^2 (-19.9%)
1971	---	---	-0.03 km^2 (-0.7%)	-0.13 km^2 (-3.1%)	-0.33 km^2 (-8.0%)
1994	---	---	---	-0.10 km^2 (-2.4%)	-0.30 km^2 (-7.3%)
2009	---	---	---	---	-0.20 km^2 (-5.0%)



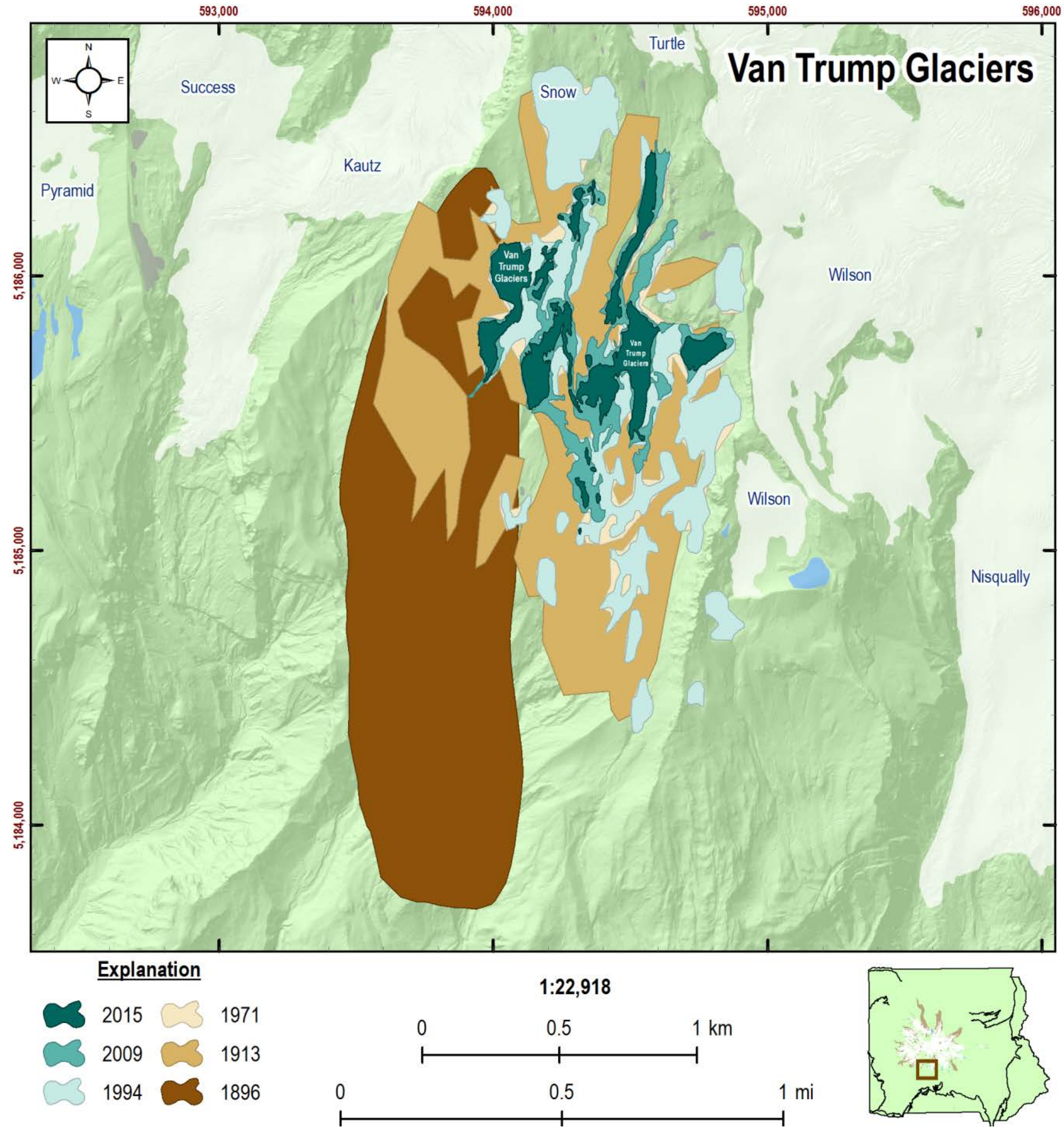
South Tahoma Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	5.93	3.43	2.92	2.23	2.21	2.00
Area, acres (ac)	1,464	847	722	552	545	495

	1913	1971	1994	2009	2015
1896	-2.50 km² (-42.2%)	-3.00 km² (-50.7%)	-3.69 km² (-62.3%)	-3.72 km² (-62.8%)	-3.92 km² (-66.2%)
1913	---	-0.51 km² (-14.8%)	-1.19 km² (-34.9%)	-1.22 km² (-35.6%)	-1.43 km² (-41.6%)
1971	---	---	-0.69 km² (-23.6%)	-0.72 km² (-24.5%)	-0.92 km² (-31.5%)
1994	---	---	---	-0.03 km² (-1.2%)	-0.23 km² (-10.3%)
2009	---	---	---	---	-0.20 km² (-9.3%)



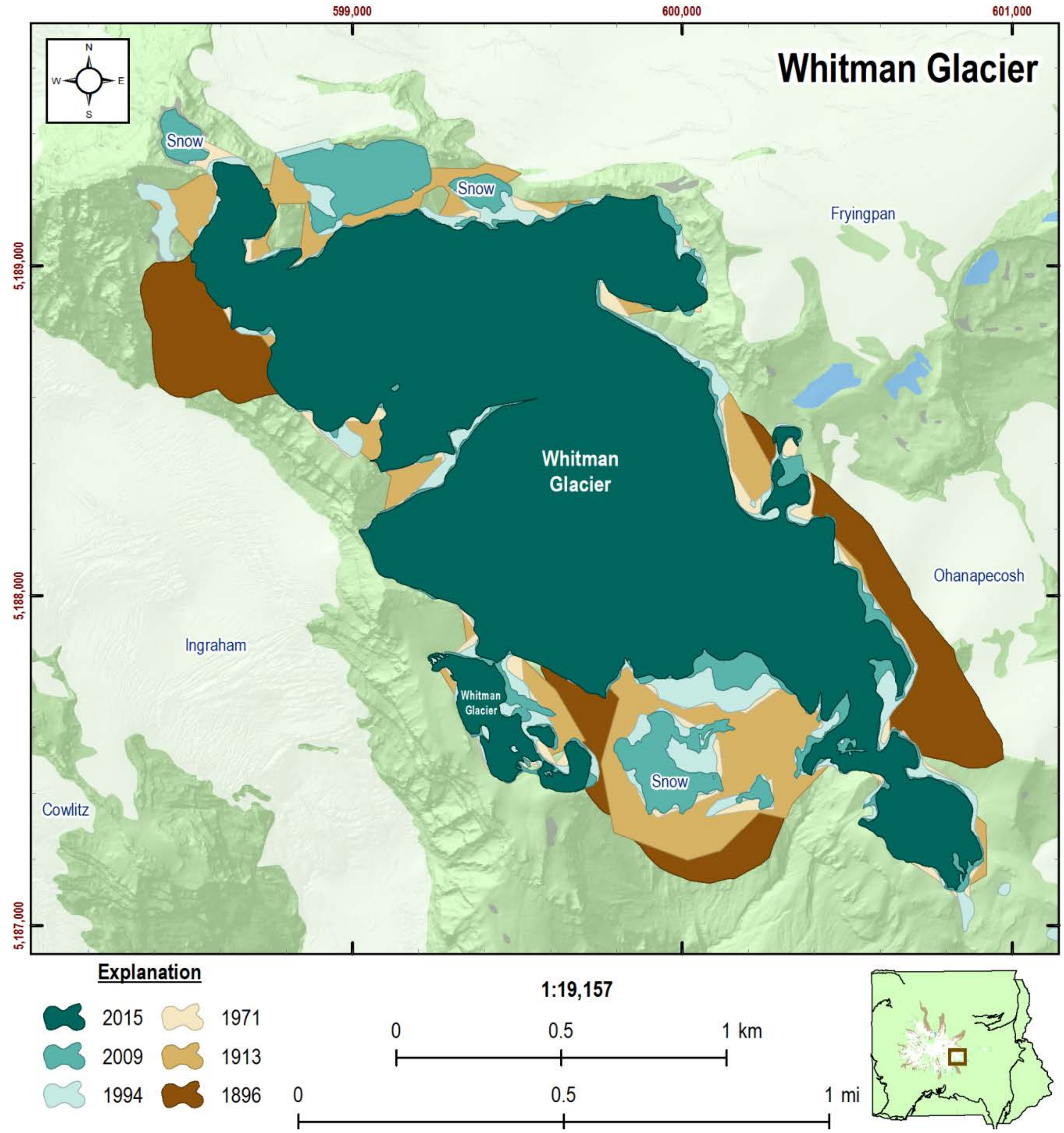
Tahoma Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	12.00	9.17	7.62	7.28	6.78	6.79
Area, acres (ac)	2,966	2,266	1,883	1,799	1,675	1,677

	1913	1971	1994	2009	2015
1896	-2.83 km² (-23.6%)	-4.39 km² (-36.5%)	-4.72 km² (-39.4%)	-5.23 km² (-43.5%)	-5.22 km² (-43.5%)
1913	---	-1.55 km² (-16.9%)	-1.89 km² (-20.6%)	-2.39 km² (-26.1%)	-2.38 km² (-26.0%)
1971	---	---	-0.34 km² (-4.4%)	-0.84 km² (-11.1%)	-0.83 km² (-10.9%)
1994	---	---	---	-0.50 km² (-6.9%)	-0.49 km² (-6.8%)
2009	---	---	---	---	+0.01 km² (+0.2%)



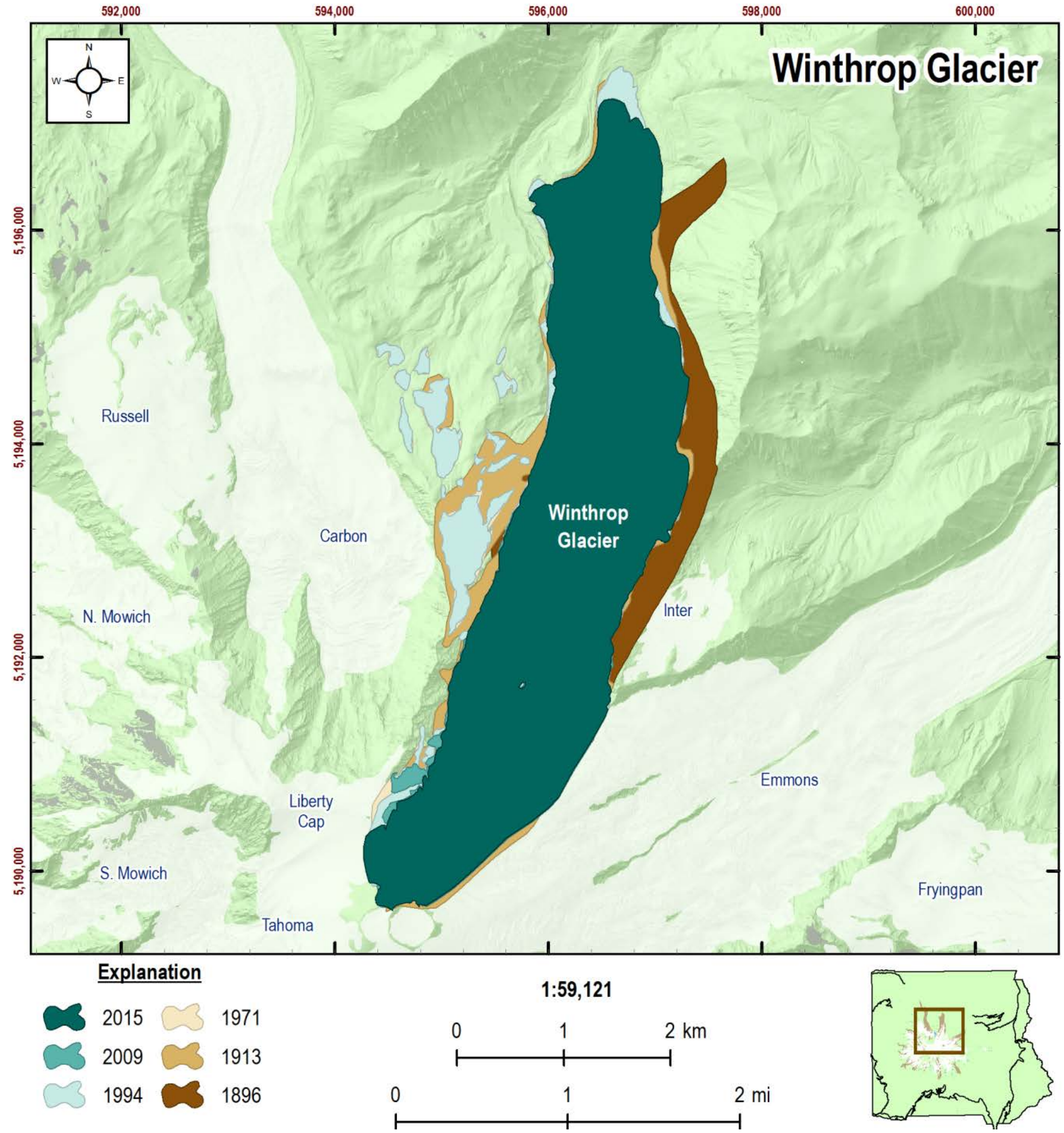
Van Trump Glaciers	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	1.44	1.40	0.68	0.72	0.32	0.18
Area, acres (ac)	355	346	168	179	78	43

	1913	1971	1994	2009	2015
1896	-0.04 km^2 (-2.5%)	-0.76 km^2 (-52.6%)	-0.71 km^2 (-49.6%)	-1.12 km^2 (-77.9%)	-1.26 km^2 (-87.8%)
1913	---	-0.72 km^2 (-51.4%)	-0.68 km^2 (-48.3%)	-1.08 km^2 (-77.3%)	-1.23 km^2 (-87.5%)
1971	---	---	+0.04 km^2 (+6.3%)	-0.36 km^2 (-53.4%)	-0.51 km^2 (-74.2%)
1994	---	---	---	-0.41 km^2 (-56.2%)	-0.55 km^2 (-75.7%)
2009	---	---	---	---	-0.14 km^2 (-44.6%)



Whitman Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	1.97	2.43	2.23	2.32	2.10	1.94
Area, acres (ac)	488	601	550	572	519	479

	1913	1971	1994	2009	2015
1896	+0.46 km² (+23.2%)	+0.25 km² (+12.7%)	+0.34 km² (+17.3%)	+0.13 km² (+6.4%)	-0.04 km² (-1.8%)
1913	---	-0.21 km² (-8.5%)	-0.12 km² (-4.8%)	-0.33 km² (-13.6%)	-0.49 km² (-20.3%)
1971	---	---	+0.09 km² (+4.0%)	-0.12 km² (-5.6%)	-0.29 km² (-12.9%)
1994	---	---	---	-0.21 km² (-9.2%)	-0.38 km² (-16.3%)
2009	---	---	---	---	-0.16 km² (-7.7%)



Winthrop Glacier	1896	1913	1917	1994	2009	2015
Area, square kilometers (km^2)	8.23	10.18	9.63	9.94	8.01	8.98
Area, acres (ac)	2,035	2,516	2,380	2,457	1,981	2,218

	1913	1971	1994	2009	2015
1896	+1.95 km^2 (+23.7%)	+1.40 km^2 (+17.0%)	+1.71 km^2 (+20.8%)	-0.22 km^2 (-2.7%)	+0.74 km^2 (+9.0%)
1913	---	-0.55 km^2 (-5.4%)	-0.24 km^2 (-2.4%)	-2.17 km^2 (-21.3%)	-1.21 km^2 (-11.8%)
1971	---	---	+0.31 km^2 (+3.2%)	-1.62 km^2 (-16.8%)	-0.65 km^2 (-6.8%)
1994	---	---	---	-1.93 km^2 (-19.4%)	-0.97 km^2 (-9.7%)
2009	---	---	---	---	+0.96 km^2 (+12.0%)

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U.S. Department of the Interior

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