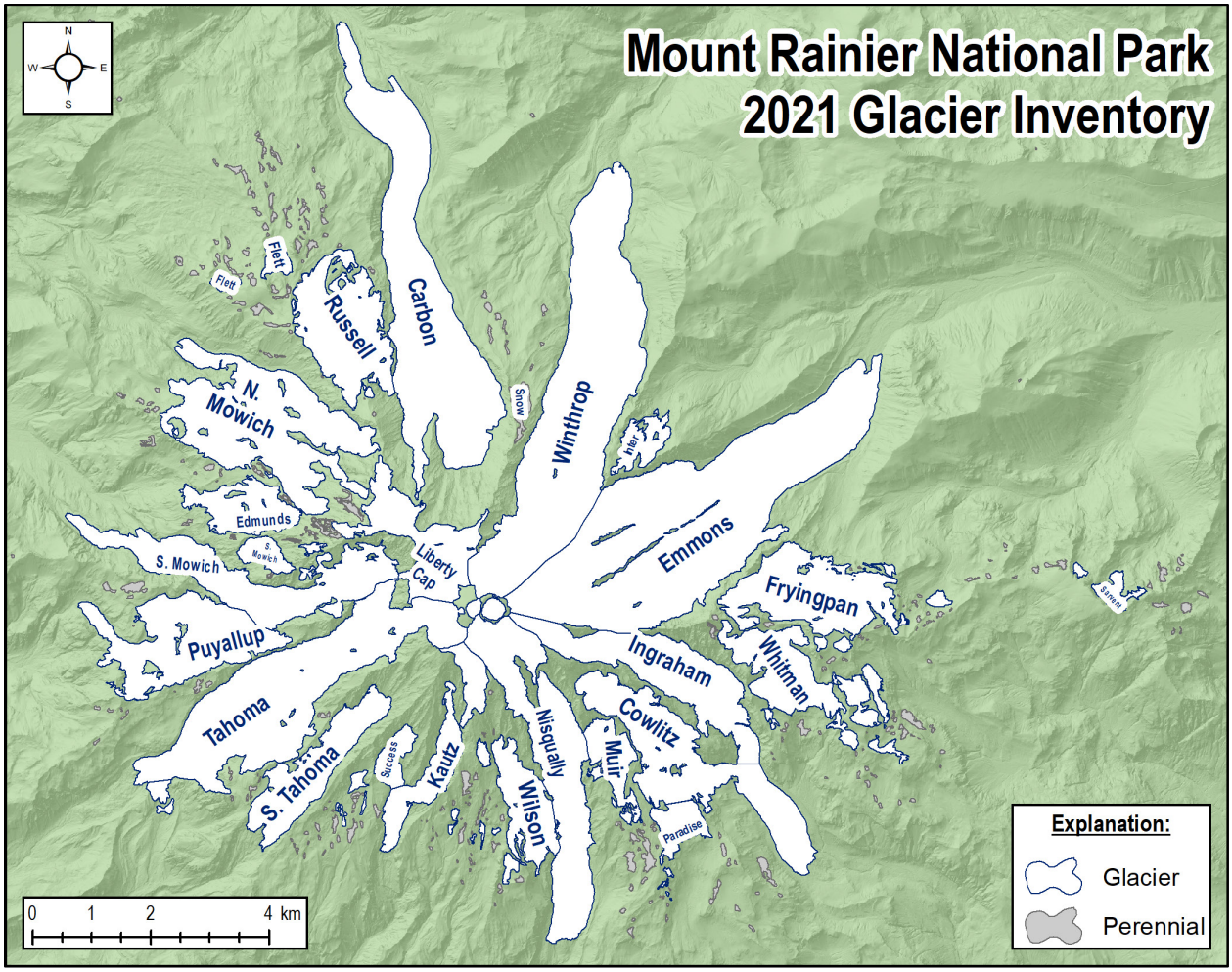
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Natural Resource Stewardship and Science

Changes in glacier extents and estimated changes in glacial volume at Mount Rainier National Park, Washington, USA from 1896 to 2021

Natural Resource Report NPS/MORA/NRR—2023/2524





ON THIS PAGE
Extents of perennial snowfields and glaciers on Mount Rainier in 2021.

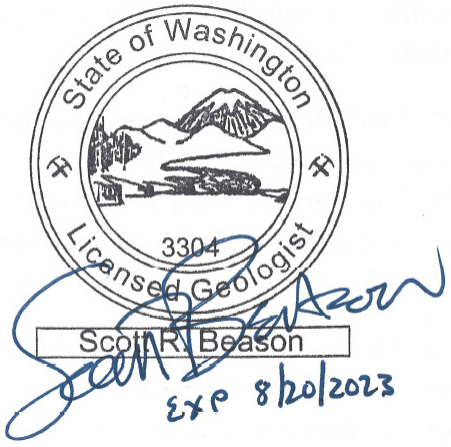
ON THE COVER
Southwest face of Mount Rainier showing the North Mowich, Edmunds, South Mowich, Puyallup, and Tahoma Glaciers from an aerial reconnaissance flight on November 21, 2021, at 15:20:46 PDT (NPS/SCOTT BEASON).

Changes in glacier extents and estimated changes in glacial volume at Mount Rainier National Park, Washington, USA from 1896 to 2021

Natural Resource Report NPS/MORA/NRR—2023/2524

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June 2023

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
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Glossary

Ablation: All processes that reduce the mass of a glacier.

Accumulation: All processes that add to the mass of a glacier.

Crevasse: A crack formed in glacier ice when tensile stresses exceed the tensile strength of the ice.

Debris Flow: A moving mass of rock fragments, soil, and mud, more than half of the particles being larger than sand size.

Firn: Snow that has survived at least one ablation season but has not been transformed into glacier ice.

Glacier: A perennial mass of ice, and possibly firn and snow, originating on the land surface by the recrystallization of snow or other forms of solid precipitation and showing evidence of past or present flow.

LiDAR (**Li**ght **D**etection **A**nd **R**anging)**:** A remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses**:** combined with other data recorded by the airborne system**:** generate precise, three-dimensional information about the shape of the Earth and its surface characteristics.

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.

Orthomosaic: A photogrammetrically orthorectified image product mosaiced from an image collection where the geometric distortion has been corrected and the imagery has been color balanced to produce a seamless mosaic dataset.

Outburst Flood: A high-magnitude, low-frequency catastrophic flood involving the sudden release of a large quantity of water. These can occur from a proglacial lake, failure of a glacier dam, rapid melting of ice sheets, collapse of glacial moraines, and/or surge of water from within a glacier.

Panchromatic: Sensitive to all visible colors of the spectrum.

Perennial: Persisting for an indefinite time longer than one year.

Snowfield: A more or less extensive and persistent mass of snow.

Structure from Motion (SfM): A photogrammetric imaging technique for estimating three-dimensional structures from two-dimensional image sequences coupled with location motion signals.

Glossary terms and definitions are from Bates and Jackson (1984) and Cogley and others (2011).

Executive Summary

Surface area of glaciers and perennial snow within Mount Rainier National Park were delineated based on 2021 aerial Structure-from-Motion (SfM) and satellite imagery to document changes to glaciers over the last 125 years. These extents were compared with previously completed databases from 1896, 1913, 1971, 1994, 2009, and 2015. In addition to the glacial features mapped at the Park, any snow patches noted in satellite- and fixed-wing- acquired aerial images in September 2021 were mapped as perennial snowfields.

In 2021, Mount Rainier National Park contained a total of 28 named glaciers which covered a total of 75.496 ± 4.109 km^2 (29.149 ± 1.587 mi^2). Perennial snowfields added another 1.938 ± 0.112 km^2 (0.748 ± 0.043 mi^2), bringing the total perennial snow and glacier cover within the Park in 2021 to 77.434 ± 4.221 km^2 (29.897 ± 1.630 mi^2). The largest glacier at Mount Rainier was the Emmons Glacier, which encompasses 10.959 ± 0.575 km^2 (4.231 ± 0.222 mi^2).

The change in glacial area from 1896 to 2021 was -53.812 km^2 (-20.777 mi^2), a total reduction of 41.6%. This corresponds to an average rate of -0.430 km^2 per year (-0.166 $mi^2 \times yr^{-1}$) during the 125-year period. Recent changes (between the 6-year period of 2015 to 2021) showed a reduction of -3.262 km^2 (-1.260 mi^2) of glacial area, or a 4.14% reduction at a rate of -0.544 km^2 per year (-0.210 $mi^2 \times yr^{-1}$). This rate is 2.23 times that estimated in 2015 (2009-2015) of -0.244 km^2 per year (-0.094 $mi^2 \times yr^{-1}$).

Changes in ice volume at Mount Rainier and estimates of total volumes were calculated for 1896, 1913, 1971, 1994, 2009, 2015, and 2021. Volume change between 1971 and 2007/8 was -0.65 km^3 (-0.16 mi^3; Sisson et al., 2011). We used the 2007/8 LiDAR digital elevation model and our 2021 SfM digital surface model to estimate a further loss of -0.404 km^3 (-0.097 mi^3). In the 50-year period between 1971 and 2021, the glaciers and perennial snowfields of Mount Rainier lost a total of -1.058 km^3 (-0.254 mi^3) at a rate of -0.021 km^3 per year (-0.005 $mi^3 \times yr^{-1}$).

The calculation of the total volume of the glaciers during various glacier extent inventories at Mount Rainier is not straightforward and various methods are explored in this paper. Using back calculated scaling parameters derived from a single volume measurement in 1971 and estimates completed by other authors, we have developed an estimate of glacial mass during the last 125-years at Mount Rainier that mostly agree with volumetric changes observed in the last 50 years. Because of the high uncertainty with these methods, a relatively modest 35% error is chosen.

In 2021, Mount Rainier's 28 glaciers contain about 3.516 ± 1.231 km^3 (0.844 ± 0.295 mi^3) of glacial ice, snow, and firn. The change in glacial mass over the 125-year period from 1896 to 2021 was -3.742 km^3 (-0.898 mi^3), a total reduction of 51.6%, at an average rate of -0.030 km^3 per year (-0.007 $mi^3 \times yr^{-1}$). Volume change over the 6-year period of 2015 to 2021 was -0.175 km^3 (-0.042 mi^3), or a 4.75% reduction, at a rate of -0.029 km^3 per year (-0.007 $mi^3 \times yr^{-1}$).

This survey officially removes one glacier from the Park's inventory and highlights several other glaciers in a critical state. The Stevens Glacier, an offshoot of the Paradise Glacier on the Park's south face, was removed due to its lack of features indicating flow, and therefore is no longer a glacier but instead a perennial snowfield. Two other south facing glaciers – the Pyramid and Van Trump glaciers – are in serious peril. In the six-year period between 2015 and 2021, these two glaciers lost 32.9% and 33.6% of their area and 42.0% and 42.9% of their volume, respectively. These glaciers are also becoming exceedingly fragmented and no longer possess what can be called a main body of ice. Continued losses will quickly lead to the demise of these glaciers in the coming decades. Overall, the glaciers on the south face of the mountain have been rapidly shrinking over the last 125 years.

Our data shows a continuation of gradual yet accelerating loss of glacial ice at Mount Rainier, resulting in significant changes in regional ice volume over the last century. The long-term impacts of this loss will be widespread and impact many facets of the Park ecosystem. Additionally, rapidly retreating south-facing glaciers are exposing large areas of loose sediment that can be mobilized to proglacial rivers during rainstorms, outburst floods, and debris flows.

Regional climate change is affecting all glaciers at Mount Rainier, but especially those smaller cirque glaciers and discontinuous glaciers on the south side of the volcano. If the regional climate trend continues, further loss in glacial area and volume parkwide is anticipated, as well as the complete loss of small glaciers at lower elevations with surface areas less than 0.2 km^2 (0.08 mi^2) in the next few decades.

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1. Introduction

Glaciers are an important geologic, geomorphic, biologic, and aquatic resource at Mount Rainier National Park (MORA) and other associated landscapes around the world. The presence of glaciers on Mount Rainier not only shapes the edifice (Lescinsky and Sisson, 1998) 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; US EPA, 2016) and downstream impacts like freshwater resources to aquatic organisms (Frans et al., 2018). 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; Cuffey and Paterson, 2006; Hooke, 2020).

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; Stevens et al., 2016; Wokosin et al., 2017; Beason et al., 2021). 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; Neiman et al., 2008; Neiman et al., 2011), and during periods extended warm surface air temperatures (Beason et al., 2021). These glacial outburst floods can quickly mobilize into debris flows due to an overabundance of loose, unstable sediment that compose steep glacial moraines. Such outburst floods and debris flows have impacted Park infrastructure and have led to changes in Park management in large geographic areas at MORA (Walder and Driedger, 1994; Beason et al., 2021).

Monitoring the changing mass of glaciers is necessary to address how climate change will affect Park resources in the future. At present, glacial monitoring at MORA encompasses the following study efforts: (1) mass balance; (2) surface elevations; (3) volume; (4) area; and (5) other miscellaneous studies.

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 et al., 2010; National Park Service, 2012; Hoffman et al., 2014; Riedel and Larrabee, 2015). Surface elevation studies on the Nisqually Glacier have been conducted yearly since the 1930s but are limited to three or four transects across the width of the glacier (Heliker et al., 1983). Volume estimates, using surface geophysical methods, are limited due to the difficulty of traversing the glacier safely (Driedger and Kennard, 1986). Surface area measurements are relatively straightforward and easy to obtain for a large area using aerial imagery (Skloven-Gill and Fountain, 2015). Other studies have been completed over the last decade to address various mechanics of glaciers, including identifying surface velocities on glaciers at the Park to delineate active and stagnant ice (Hodge, 1974; Heliker, et al., 1983; Walkup et al., 2019; Todd et al., 2021), mapping supraglacial debris for a variety of purposes (Dits and Moore, 2013; Moore et al., 2014; Basehart et al., 2017; Moore et al., 2019; Fontana et al., 2021; Ireson et al., 2021), methods for remotely monitoring glaciers (Medley, 2008; Shean, 2017; Whorton et al., 2017a;

Todd et al., 2022) and time-lapse photography to document glacial motion (Beason and Kenyon, 2018).

This study documents changes in surface area for glaciers and perennial snowfields at MORA. This study builds on extents of glaciers acquired in 1896, 1913, 1971, 1994, 2009, and 2015 (Russell, 1897; Matthes, 1914; Nylen, 2001; Robinson et al., 2010; Beason, 2017; George and Beason, 2017). Like the 2015 season, the 2021 season proved to be an ideal year to study the changes in glacial extent due to a low snow year and presence of clear, high-resolution (less than 0.4 m [1.3 ft] per pixel) satellite- and airborne-acquired aerial imagery which allowed the delineation of glaciers and perennial snowfields.

This work compliments other recent studies on glacial loss in the Cascade Range, including volcanoes like Glacier Peak (Fordham, 2022), Mount Adams (Sitts et al., 2010), Mount Baker (Pelto, 2015), Mount Hood (Ellinger, 2010) and glaciers within Olympic National Park (Riedel et al., 2015; Fountain et al., 2022) and North Cascades National Park (Granshaw and Fountain, 2006; Pelto, 2008; Dick, 2013; Pelto, 2015; Riedel and Larrabee, 2016; Headman et al., 2017; Pelto, 2017; Whorton et al., 2017b). Nearly all glaciers in the Cascade Range are retreating and thinning, with a notable exception of the Crater Glacier at Mount St. Helens (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) and losing half of their glacial area since 1900 (Fountain et al., 2022). 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 have seen some of the most drastic retreats in the entire region. Between 1900 and 2009, the glacial area in the North Cascades 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 et al., 2015; Riedel and Larrabee, 2016).

2. 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 more than about 10% of the total ice area in the lower 48 states (Meier, 1998; Fountain et al., 2017). Given its proximity to the Pacific Ocean, prevailing westerly winds, and significant topographic prominence, Mount Rainier is a substantial orographic barrier that increases precipitation locally, compared to adjacent lowland areas. At higher elevations, more snow accumulates than melts, which creates the glaciers.

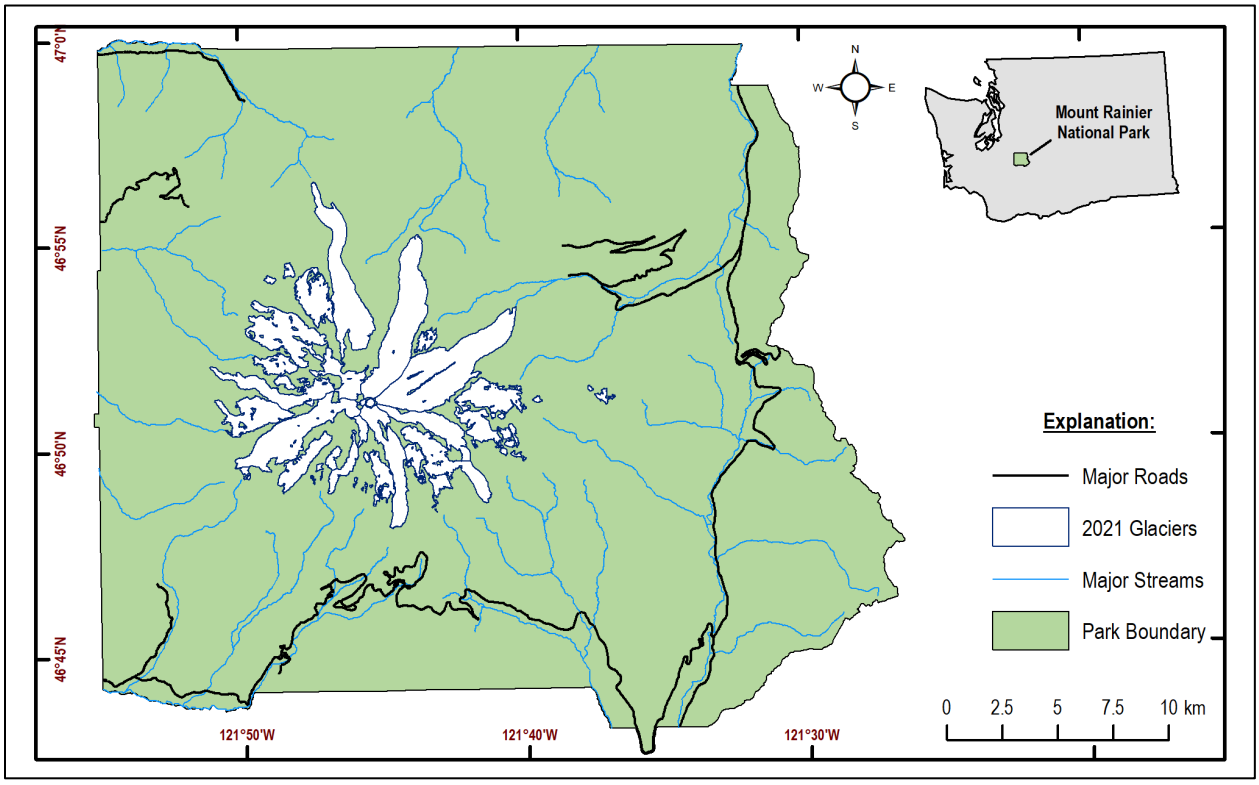


Figure 1. Mount Rainier National Park extent and study area.

Glaciers at Mount Rainier vary considerably in size, elevation range, and aspect. Those glaciers on the north side of Mount Rainier are generally larger and have more volume (Driedger and Kennard, 1986). Glaciers are present at elevations between 1,100 m (3,600 ft) and 4,392 m (14,410 ft). Glaciers and perennial snowfields account for approximately 8.5% of the total area of MORA.

Mount Rainier has been episodically active in the last 500,000 years, including at least 10 to 12 eruptions in the last 2,600 years (Sisson and Vallance, 2009). The mass of glaciers on Mount Rainier highlights one of its largest geological hazards – lahars (Scott et al., 1995). Lahars (volcanic debris flows) have occurred frequently at Mount Rainier over the past several thousand years and can recur without warning, possibly triggered by earthquakes or by changes in the volcano's hydrothermal

system (Scott et al., 1995). Eruptions at Mount Rainier have initiated large lahars that have inundated the Puget Lowland as far as 100 km (62 mi) from the volcano (Crandell, 1971). Because of its far-reaching lahar hazards, MORA has a “very high” threat and ranks as the third most hazardous volcano in the nation (Ewert et al., 2018). In addition to these far-reaching lahars, local-scale debris flows induced by hydrologic and surficial geomorphic processes represent a significant and frequent management concern within MORA boundaries (Driedger and Fountain, 1989; Driedger and Walder, 1991; Walder and Driedger, 1994; Scott and Vallance, 1995; Vallance et al., 2003).

3. Previous Research

Glacier extents have been mapped during the last 125 years at Mount Rainier. While individual glaciers were mapped prior to the 1890s (King, 1871), the first dataset available for the entire Park was completed in 1896 (Russell, 1897; Figure 2). Subsequent parkwide glacier mapping occurred in 1913, 1971, and 1994 (Matthes, 1914; Nylen, 2001). 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 that point (Robinson et al., 2010).

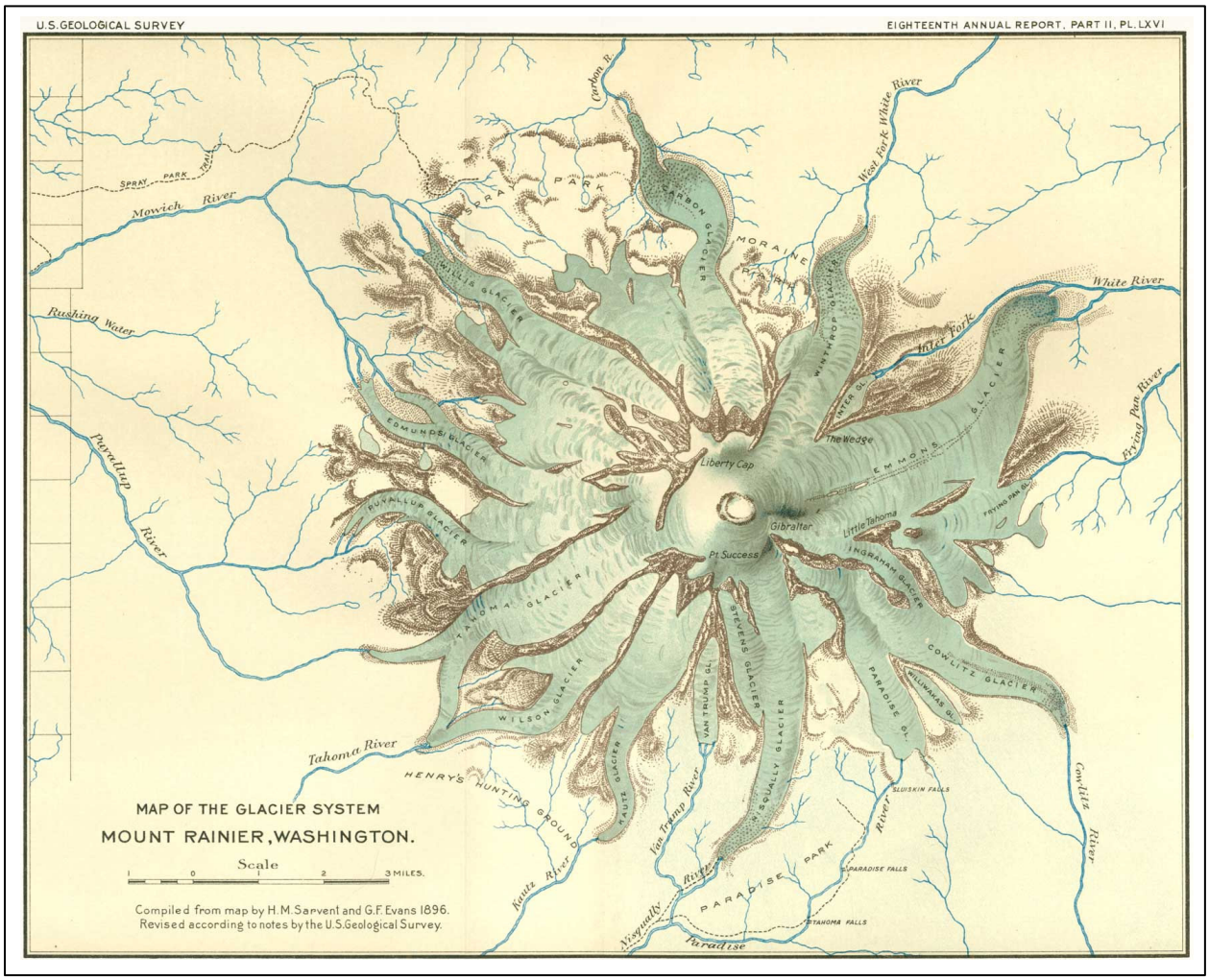


Figure 2. The first comprehensive mapping of glaciers on Mount Rainier in 1896 (modified from Russell, 1897). Note that several glaciers are missing from the map (e.g., Ohanapecosh, Whitman, Flett, etc.) or are mislabeled (e.g., Stevens Glacier on the map is actually the Wilson Glacier, and the Wilson Glacier on the Map is actually the South Tahoma Glacier).

The latest glacial extent update was based on the 2015 glacial extent as observed via satellite and aerial imagery in an especially warm and low-snowpack year (Beason, 2017; George and Beason, 2017).

The older maps in 1896 and 1913 had poor spatial accuracy indicated by the offset of some topographic features observed on modern maps. For example, the 1896 inventory show glaciers which cross over significant topographic breaks (e.g., the lower Puyallup Glacier) and boundaries between glaciers that do not match with modern mapping.

Glacial volume has only been directly measured one time in the Park's history by Driedger and Kennard (1986), using glacial extents from 1971 and surveys of ice thickness from ice penetrating radar, corrected for slope, and used to develop subglacial contour maps from which glacial volumes were calculated. This approach was used not only at MORA, but also at Mount Hood, Three Sisters, and Mount Shasta volcanoes.

Other authors have estimated glacial volume using a volume-area scaling approach (Nylen, 2001). Much research has been conducted with respect to this technique (Bahr et al., 1997; Bahr et al., 2015; Radić et al., 2017). Bahr and others (2015) note that "over 60 papers since 1988 have been published in the glaciological and environmental change literature containing applications of volume-area scaling" for a variety of purposes. Bahr and others (2015) note some major misconceptions and inappropriate applications for this type of analysis.

In contrast, volume change can be estimated more precisely by differencing digital elevation models. This approach was first completed at MORA by Robinson and others (2010) and Sisson and others (2011). These methods are interesting because they provide a high-confidence numeric change in glacial volume between time periods which can help determine the accuracy of volume-area scaling approaches used later in this paper.

4. Methods

4.1. Glacier Extent Delineation and Comparison with Previous Studies

Mapping of 2021 extents was completed by hand digitizing the glacier and perennial snow perimeter from aerial imagery at a 1:1,000 scale in a similar manner to the 2015 glacier extent and debris cover layers (Beason, 2017). In situations where perimeters were not clearly observable, 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, and crevasses. Glaciers that shared a common boundary (e.g., the Emmons and Winthrop glaciers) maintained the position of the boundary from previous surveys in situ order to minimize area changes because of shifting borders. Field verification was undertaken where possible. Due to the large aerial expanse of this inventory, field verification targeted areas of safe access and ambiguity and was not completed for all glaciers.

Aerial images were acquired over the entire Park from a fixed wing parkwide Structure from Motion (SfM) flight conducted by Owyhee Air Research that occurred between September 21 to 24, 2021. The images were high resolution (0.253-0.337 m [0.831-1.1.06 ft]) and panchromatic with a source resolution of 1:961 to 1:1,274. A photographic orthomosaic of the entire Park was pinned to the surface with ground control points. A digital surface model (DSM) was constructed from the panchromatic imagery using Structure from Motion (SfM) methods (Shean et al., 2016). A DSM differs from products like bare-earth LiDAR digital elevation models (DEM) in that the DSM product cannot "see through" vegetation. This product would be similarly called a "highest hit" LiDAR image since it only can see unvegetated features or vegetation and ground use. The lack of a bare earth product here is not a concern in the alpine zone due to little or no canopy and vegetative cover.

Two separate orthomosaics were developed from the 21-24 September 2021 SfM flights (Table 1). The "`MORAsfm_WestOrthomosaic_20210921`" file covers the western bound and high-mountain areas of MORA. This set is the primary imagery used to map glaciers and snow in the Park due to its more comprehensive coverage of the alpine zone but does not fully cover the eastern flanks. The National Standard for Spatial Data Accuracy (NSSDA) horizontal accuracy of the orthomosaic is 0.337 m (1.106 ft) with a source resolution of 1:1,274 and was assembled from images acquired from the 21 September 2021 flight. The "`MORAsfm_EastOrthomosaic_2021092324`" file covers the northern, southern, and eastern bounds of MORA with partial coverage of the eastern flank of the volcano. This set has the overlap needed to complete the eastern sections not observed during the western collections day (21 September 2021) such as the lower Emmons, Winthrop, Fryingpan, Ohanapecosh, Sarvent, and Whitman glaciers. The NSSDA horizontal accuracy of the orthomosaic is 0.253 m (0.830 ft) with a source resolution of 1:961 and was assembled from images acquired from the 23-24 September 2021 flights.

Associated with the two orthomosaics, two separate DSM files were assembled using standard SfM methods and Agisoft Metashape software (Table 1). The

"MORAsfm_DSM_Orthometric_20210921" DSM file has a pixel resolution of 0.674 m (2.211 ft), NSSDA horizontal accuracy of 0.343 m (1.125 ft), and NSSDA vertical accuracy of 0.376 m (1.234 ft). This file is associated with the orthomosaic acquired on 21 September 2021. The "MORAsfm_DSM_Orthometric_2021092324" file has a pixel resolution of 0.508 m (1.667 ft), NSSDA horizontal accuracy of 0.420 m (1.378 ft), and NSSDA vertical accuracy of 0.310 m (1.017 ft). This file is associated with the orthomosaic acquired on 23-24 September 2021.

Table 1. Images and DSM files used in the delineation of glaciers in 2021 at Mount Rainier. The order of the files corresponds to the review order in delineation.

File Name	Type	Horizonal Accuracy	Vertical Accuracy	Pixel Resolution	Scale
MORAsfm_EastOrthomosaic_2021092324	Image	0.253 m	–	–	1:961
MORAsfm_WestOrthomosaic_20210921	Image	0.337 m	–	–	1:1,274
PierceCountyNAIP_2021	Image	–	–	0.600 m	1:2,268
MORAsfm_DSM_Orthometric_20210921	DSM	0.343 m	0.376 m	0.674 m	–
MORAsfm_DSM_Orthometric_2021092324	DSM	0.420 m	0.310 m	0.508 m	–
PlanetScope_20210901	Image	–	–	3.000–3.500 m	–

The SfM flights at the Park occurred just after the first snow accumulation in MORA's upper elevations. Because of this, we employed two other image sources to help define glacier perimeters (Table 1): (1) "PierceCountyNAIP_2021" – the USDA Forest Service's National Agriculture Image Program (USFS NAIP) images for Pierce County, WA, collected during a regular acquisition cycle between 23-24 July 2021 for the Park, with a corresponding pixel resolution of 0.6 m (1.97 ft) and source resolution of 1:2,268; and (2) "PlanetScope_20210901" – Planet Labs satellite imagery of the Park from 01 September 2021, with a corresponding resolution of 3-3.5 m (9.8-11.5 ft).

Data were reviewed in the following order to preserve the highest possible polygon accuracy (Table 1):

1) MORAsfm_EastOrthomosaic_2021092324
2) MORAsfm_WestOrthomosaic_20210921
3) PierceCountyNAIP_2021
4) MORAsfm_DSM_Orthometric_20210921
5) MORAsfm_DSM_Orthometric_2021092324
6) PlanetScope_20210901

In some cases, we rendered imagery in 3D using ArcPro Scene functions to view fine-scale textural differences to improve our view in difficult or seemingly featureless areas. Each mapped glacial or perennial snowfield also includes attributes described in Table 2.

Table 2. Attribute information for each delineated glacier or perennial snowfield in 2021.

Field Name	Description	Example
Id	A unique identification number	23
ShortName	Short name, useful in small-scale maps	S. Tahoma
FullName	Full name, useful in large-scale maps	South Tahoma Glacier
Area_m2	Area in square meters	1947002.35639
Area_ft2	Area in square feet	20957275.2129
FeatType	Enumerated value that indicates the type of feature; Glacier or Perennial	Glacier
Watershed	The watershed that the feature resides in	Tahoma
ImageSourc	Image source used to determine the extents of the feature's area (possible values listed in Table 1)	2021.09.21_SfM; 2021 NAIP; 2021.09.01_PlanetScope
ElevationS	Elevation data source used to help determine the extents of the feature's area (possible values listed in Table 1)	2021.09.21_DSM
HasCrevass	Integer that states if the feature has crevasses (1) or does not (0)	1
EditedBy	Initials of the primary digitizer	LJW
QC	Initials of the primary quality control review	TRK
Shape_Leng	Length of the shape's outline, in meters	11223.779319
Shape_Area	Area of the shape, in square meters (a repeat of the Area_m2 field)	1947002.36539

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 1897 inventory only lists the Cowlitz Glacier and does not individually name the Ingraham Glacier. When comparing the 2021 inventory with older inventories that used glacier systems, the individual 2021 glaciers were added together to match the glacier systems. Like the 2015 study (Beason, 2017), all individual glaciers in the Park have their own feature or features. Topographic information from the 2007/2008 LiDAR dataset and 2021 SfM DSMs was used to help identify topographic breaks that were used to delineate ice divides between adjoining glaciers.

4.2. Glacier Statistics

The DSM datasets described in Section 4.1 were used to calculate topographic characteristics of individual glaciers delineated in 2021. The topographic data was clipped to each delineated glacier to determine maximum and minimum elevations for each glacier using the *Zonal Statistics* tool in ArcGIS. Total relief is the range between minimum and maximum elevations for each glacier. Glacier length is the distance along a line from the most upstream to most downstream point on each glacier, while broadly following curves or bends in the glacier. Average slope (degrees) was calculated using the *Slope* tool in ArcGIS, summarized per glacier with the *Zonal Statistics* tool (ESRI, 2016).

Average flow direction was calculated using the ArcGIS' *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 glacier yields average flow direction for that glacier. Prior to calculating flow direction, the DSM is "filled" to correct for sinks and other small imperfections in the data (ESRI, 2016). Individual glaciers were extracted from the Flow Direction layer using the *Extract by Mask* tool leaving a raster layer with flow directions for each cell.

The average flow direction for each glacier, $\bar{\alpha}$, was calculated by Equation 1:

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

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 using this formula. 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, crevasses, and ice deformation.

4.3. Uncertainty of 2021 inventory

Digitizing glacial boundaries from remote imagery introduces a number of errors, including: (1) georeferencing uncertainty of the image; (2) accuracy of digitizing the perimeter; and (3) interpretation uncertainty. DeVisser and Fountain (2015) regard the later as the most significant because of poor image quality, debris cover, and snow.

Imagery errors depend on the source of the image. For example, some 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, 1999). 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) based on the USGS nomenclature.

Total 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 Equation 2:

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

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 (Carisio, 2012); generally, smaller glaciers have a higher variability error (Post et al., 1971; Sitts et al., 2010; Riedel et al., 2015; Riedel and Larrabee, 2016). For the purposes of this study, a relatively high 5% value was used for potential variability error in Equation 3:

$$E_2 = 0.05A_i$$

Total surface area error, E, is therefore calculated as the following in Equation 4:

$$E = E_1 + E_2$$

4.4. Volumetric Change of Glaciers – Measurements from DEMs and DSMs

Estimates of total change in glacial volume is a relatively easy measurement when provided with digital elevation models and using tools in geographic information software. Sisson and others (2011) used a National Elevation Dataset digital elevation model from 1:24,000 topographic maps produced by photogrammetry of September 1970. The digital elevation map was then compared to the 2007/8 LiDAR dataset acquired for the Park (Watershed Sciences, 2009). Differencing the DEMs yields a total loss of elevation change at individual points on the glacier, which can then be summed to calculate a volume loss per glacier.

A similar approach was used to summarize the volume loss between 2007/8 LiDAR and the 2021 SfM DSM. The differencing in this step was clipped to the 2009 glacier extent to summarize the changes in glacial and proglacial areas between 2009 and 2021 (since there was no advance in glaciers in this period; otherwise, the 1971 extent would be utilized).

4.5. Total Glacial Volume – Statistical Methods

The extrapolation of glacial volume from glacial area is possible, but may depend on up to 12 factors, including glacier dimensions, density, velocity, slope, aspect, and others (Bahr et al., 1997; Bahr et al., 2015). Some authors suggest that a simple power law relationship with a scaling exponent, γ, and scaling parameter, c, can provide an approximation of simplified glacial volume, V, from mapped areas, A (Chen and Ohmura, 1990; Bahr et al., 2015; Radić et al., 2017) in Equation 5:

$$V = c\,A^{\gamma}$$

Bahr and others (2015) argue, on theoretical grounds, that the scaling exponent, γ, is a constant of 1.375. The scaling parameter, c, can vary as necessary to account for climatic region, topographic setting, or other factors. Bahr and others (2015) have a lengthy discussion about the area-volume scaling approach, and it is worth referencing when determining the usefulness of glacial volumes presented in this paper.

Driedger and Kennard's (1986) estimates of glacial volume, for the largest glaciers in the Park, provides a useful baseline. Some glaciers measured by Driedger and Kennard (1986) had very few points, and some parts of individual glaciers could not be accessed due to crevasses, ice falls, and steep topography. As such, some estimates of individual glacial volume are better than others. They used ice penetrating radar to measure ice depth and individual points and developed subglacial contour maps. From these contour maps, the authors calculated volumes for each glacier and developed two separate populations of glaciers and equations to determine volume from physical statistics of each glacier.

To calculate volume, V, of glaciers longer than 2,591 m (8,500 ft), Driedger and Kennard (1986) suggest using Equation 6:

$$V = \frac{\tau}{\rho g} \sum_{i=0}^{n} \left(\frac{A_i}{\cos \alpha_i \ \sin \alpha_i} \right)$$

Where τ is the basal shear stress (Equation 7), ρ is the average density of glacial ice (1.779 slug/ft^3), g is the acceleration of gravity (32.178 ft/s^2), A_i is the area of the glacier in 304.8 m (1,000 ft) contour intervals, and α_i is the average slope for the glacier in 304.8 m (1,000 ft) contour intervals. It should be noted that this equation uses imperial values and not metric (e.g., areas in ft^2, gravity in ft/s^2, etc.). This method divides a glacier into n 304.8 m (1,000) foot intervals with area and slope calculated for each interval (for example, the Carbon Glacier in 2021 would have 10 individual intervals from 3,617 ft to 12,212 ft).

Basal shear stress is calculated as Equation 7:

$$\tau = 451.12 \left(\sum_{i=0}^{n} \left(\frac{A_i}{\cos \alpha_i} \right) \right)^{1.124}$$

This equation uses the same area and slope variables and units measured over the 304.8 m (1,000 ft) contour intervals.

For glaciers shorter than 2,591 m (8,500 ft), Equation 5 is modified to Equation 8:

$$V = 9.62 \, A^{1.124}$$

Where A is the area of the entire glacier surface (not split into 304.8 [1,000 ft] segments).

This approach worked well for Driedger and Kennard (1986), however, application to subsequent glacier mappings in 2009 and 2021 showed that in some cases, small glaciers in 2021 had a greater volume than the larger glacier (by area) in 2009. This indicates that Equations 6 and 8 were tuned to those specific glacier configurations encountered by Driedger and Kennard (1986) and a more generally applicable equation is needed.

We generalize the statistical approach by using the volumes determined by Driedger and Kennard (1986), and Equation 5 using Bahr's stated scaling exponent to estimate, c_i, for individual glaciers in Equation 9:

$$c_i = \frac{V_i}{A_i^{1.375}}$$

Results show (Table 3) that the global mean of the of the scaling parameter, c, 0.034 (Bahr et al., 2015), falls within the minimum and maximum of our estimated values.

Table 3. Calculation of glacier-specific scaling parameter, c, from estimates of glacial area and volume in 1971 from Driedger and Kennard (1986). Areas and volumes in imperial units come directly from Table 2 in Driedger and Kennard (1986, Page 13).

Glacier Name	Area (ft^2 x10^6)	Volume (ft^3 x10^9)	Area (km^2)	Volume, (km^3)	Scaling Parameter (*c*)
Carbon	85.2	21.5	7.915	0.711	0.041
Columbia Crest[1]	–	–	–	–	0.027
Cowlitz	36.8	6.0	3.419	0.170	0.031
Edmonds	15.0	1.1	1.394	0.031	0.020
Emmons	120.2	23.8	11.167	0.674	0.024
Flett	3.2	0.2	0.297	0.006	0.030
Fryingpan	35.2	2.9	3.270	0.082	0.016
Ingraham	42.6	7	3.958	0.198	0.030
Inter	8.4	0.6	0.780	0.017	0.024
Kautz	12.4	1.3	1.152	0.037	0.030
Liberty Cap	1.7	0.1	0.158	0.003	0.036
Muir	10.1	0.7	0.938	0.020	0.022
Nisqually	49.7	7.8	4.617	0.221	0.027
North Mowich	66.4	9.5	6.169	0.269	0.022
Ohanapecosh	17.3	1.3	1.607	0.037	0.019
Paradise	10.9	0.8	1.013	0.023	0.022
Puyallup	54.8	10.2	5.091	0.289	0.030
Pyramid	5.8	0.4	0.539	0.011	0.026
Russell	35.5	3.1	3.298	0.088	0.017
Sarvent	6.2	0.4	0.576	0.011	0.024

[1] A scaling parameter could not be calculated for the Columbia Crest Glacier based on data from Driedger and Kennard (1986). We use the average scaling parameter of 0.027 for all glaciers in the Park to fill this void.

[2] A scaling parameter was not established for the Stevens Glacier specifically, and we use the scaling parameter established for the Paradise Glacier.

[3] Tahoma was split into a Nisqually and Paradise drainage basin in Driedger and Kennard (1986). We sum the area and volume for the glacier to create a scaling parameter for the entire glacier.

Table 3 (continued). Calculation of glacier-specific scaling parameter, *c*, from estimates of glacial area and volume in 1971 from Driedger and Kennard (1986). Areas and volumes in imperial units come directly from Table 2 in Driedger and Kennard (1986, Page 13).

Glacier Name	Area (ft^2 x10^6)	Volume (ft^3 x10^9)	Area (km^2)	Volume, (km^3)	Scaling Parameter (*c)*
South Mowich	38.4	4.5	3.567	0.127	0.022
South Tahoma	30.4	4.6	2.824	0.130	0.031
Stevens[2]	–	–	–	–	0.022
Success	7.4	0.5	0.687	0.014	0.024
Tahoma[3]	92.9	16.1	8.631	0.456	0.024
Van Trump	6.7	0.5	0.622	0.014	0.027
Whitman	23.8	4.4	2.211	0.125	0.042
Wilson	15.5	1.9	1.440	0.054	0.033
Winthrop	98.1	18.5	9.114	0.524	0.025
Total:	**1,023.5**	**169.4**	**95.086**	**4.341**	**n/a**
Average:	**n/a**	**n/a**	**n/a**	**n/a**	**0.027**
Minimum:	**n/a**	**n/a**	**n/a**	**n/a**	**0.016**
Maximum:	**n/a**	**n/a**	**n/a**	**n/a**	**0.042**

[1] A scaling parameter could not be calculated for the Columbia Crest Glacier based on data from Driedger and Kennard (1986). We use the average scaling parameter of 0.027 for all glaciers in the Park to fill this void.

[2] A scaling parameter was not established for the Stevens Glacier specifically, and we use the scaling parameter established for the Paradise Glacier.

[3] Tahoma was split into a Nisqually and Paradise drainage basin in Driedger and Kennard (1986). We sum the area and volume for the glacier to create a scaling parameter for the entire glacier.

We use Equation 5 with the parameters in Table 3 to calculate glacier volumes for all years we have glacier area. There are some obvious caveats with this method, most importantly that this is based on extents from 1971 and volume estimates from a single point in time (between 1971 and 1981).

The other volume-area scaling referenced in this paper is based on work by Nylen (2001). In his thesis, Nylen uses a similar power log function to Equation 5. However, when we attempted reanalysis of this data, the scaling parameter of 0.175 and scaling exponent of 1.36 referenced in the thesis (Nylen, 2001, page 19) generate volumes that are about an order of magnitude higher than presented later in the thesis. Since Table 7 (area) and Table 13 (volume) in the thesis (Nylen, 2001, page 39 and 48, respectively) had values for 1913, 1971, and 1914, we used these values to recalculate the scaling parameter for the areas presented in each survey period (we left the scaling exponent of 1.36 in this approach). This recalculated equation is shown in Equation 10:

$$V = 0.0255\, A^{1.36}$$

When plotted (see section 5.6, "Glacial Volume Change – 1896 to 2021"), Nylen's method (Equation 10) tends to plot lower than the Driedger and Kennard scaling method (Equation 5 with scaling

parameters from Table 3). Therefore, we consider the Nylen method to fall toward a lower estimate of glacial volume, while the Driedger and Kennard scaling method rises toward a higher estimate of glacial volume. An average of glacial volume, V_i, for each period can be calculated per glacier (i) by Equation 11:

$$V_i = \frac{\left(c_i {A_i}^{1.375}\right) + \left(c_n {A_i}^{1.36}\right)}{2}$$

Where c_i is the glacier-specific scaling parameter from Table 3, c_n is the back-calculated scaling parameter from Nylen (2001) of 0.0255, and A_i is the extent of the glacier in each period (units are in metric). The total glacial volume per period can then be summed.

Error in these methods (Equation 5, 10 and 11) are uncertain, but could range wildly depending on many parameters, and are based on only one point measurement by Driedger and Kennard (1986). Driedger and Kennard (1986) discuss error in their approach and state that the conservative estimate for error in the volume of measured glaciers is ± 20%. Factoring in Nylen's (2001) work, which relates error in glacier extent as a function of glacial perimeter (Figure 4 in Nylen, 2001, Page 23), we estimate that our error is approximately ± 35%. Until better estimates of the relationship between glacial area and volume are determined for the Park, the values presented in this report should only be used with caution.

5. Results and Analysis

5.1. Glacier Area

The total glacier covered area on Mount Rainier in 2021 is 75.496 ± 4.109 km^2 (29.149 ± 1.587 mi^2) and varied in size from 0.117 km^2 (0.045 mi^2) to 10.959 km^2 (4.231 mi^2), averaging 2.696 km^2 (1.041 mi^2) (Figure 3; Table 4). As noted in previous sections, the Stevens Glacier was removed from the Park inventory due to a lack of discernible flow characteristics and its small size. Four glaciers had areas greater than 5 km^2 (1.93 mi^2) totaling 33.207 km^2 (12.821 mi^2), accounting for 43.99% of the total glacier area on Mount Rainier. Thirteen glaciers had a surface area less than 1.5 km^2 (0.58 mi^2); the remainder (12) had an area between 1.5 km^2 and 5 km^2 (0.58 mi^2 and 1.93 mi^2). Unnamed perennial ice and snowfields had a total area of 1.938 ± 0.112 km^2 (0.748 ± 0.043 mi^2). The total volume of year-round snow and ice in 2021 at Mount Rainier was 77.434 ± 4.221 km^2 (29.897 ± 1.630 mi^2). Maps and details of individual glaciers are shown in Appendix A.

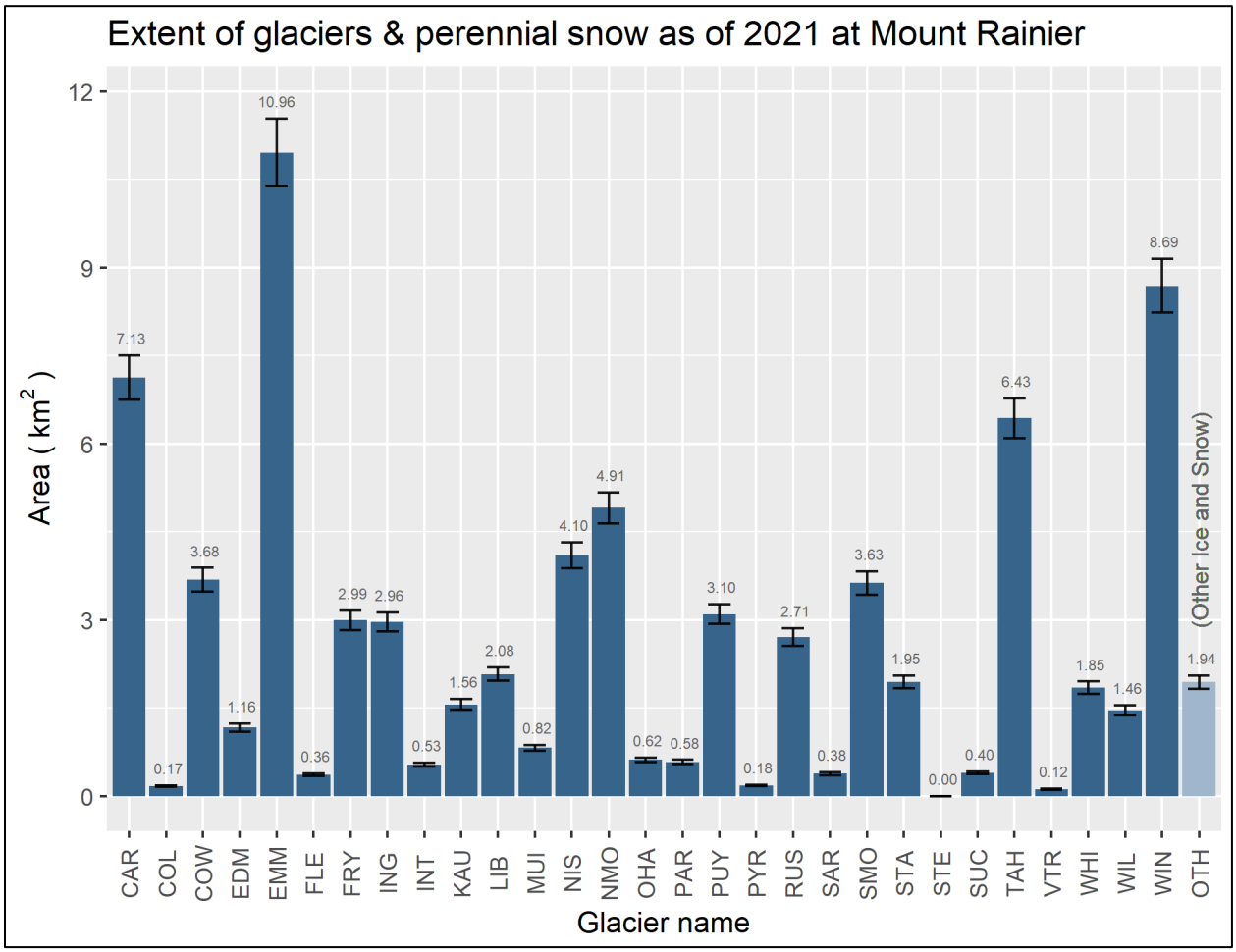


Figure 3. Extent of perennial snow and glaciers at Mount Rainier in 2021, based on data in Table 4. The value at the top of each column is the total surface extent of each glacier. Abbreviations for glacier names can be found in Table 4.

Table 4. Extent of glacial ice and perennial snowfields in 2021 at Mount Rainier.

Glacier name	Ident	Rank	2021 aerial extent of glacial ice, snowfields, or perennial snow		
			m^2	km^2	mi^2
Carbon	CAR	3	7,127,273 ± 378,438	7.127 ± 0.378	2.752 ± 0.146
Columbia Crest	COL	27	172,250 ± 12,044	0.172 ± 0.012	0.067 ± 0.005
Cowlitz	COW	7	3,684,615 ± 200,102	3.685 ± 0.200	1.423 ± 0.077
Edmunds	EDM	18	1,164,597 ± 67,153	1.165 ± 0.067	0.450 ± 0.026
Emmons	EMM	1	10,959,203 ± 575,333	10.959 ± 0.575	4.231 ± 0.222
Flett	FLE	25	362,938 ± 23,128	0.363 ± 0.023	0.140 ± 0.009
Fryingpan	FRY	10	2,993,296 ± 163,970	2.993 ± 0.164	1.156 ± 0.063
Ingraham	ING	11	2,962,359 ± 162,349	2.962 ± 0.162	1.144 ± 0.063
Inter	INT	22	532,465 ± 32,657	0.532 ± 0.033	0.206 ± 0.013
Kautz	KAU	16	1,560,988 ± 88,380	1.561 ± 0.088	0.603 ± 0.034
Liberty Cap	LIB	13	2,075,612 ± 115,693	2.076 ± 0.116	0.801 ± 0.045
Muir	MUI	19	822,523 ± 48,625	0.823 ± 0.049	0.318 ± 0.019
Nisqually	NIS	6	4,102,234 ± 221,859	4.102 ± 0.222	1.584 ± 0.086
North Mowich	NMO	5	4,906,908 ± 263,661	4.907 ± 0.264	1.895 ± 0.102
Ohanapecosh	OHA	20	615,664 ± 37,271	0.616 ± 0.037	0.238 ± 0.014
Paradise	PAR	21	580,582 ± 35,329	0.581 ± 0.035	0.224 ± 0.014
Puyallup	PUY	9	3,097,562 ± 169,431	3.098 ± 0.169	1.196 ± 0.065
Pyramid	PYR	26	176,038 ± 12,271	0.176 ± 0.012	0.068 ± 0.005
Russell	RUS	12	2,705,734 ± 148,888	2.706 ± 0.149	1.045 ± 0.057
Sarvent	SAR	24	380,425 ± 24,993	0.380 ± 0.025	0.147 ± 0.010
South Mowich	SMO	8	3,626,252 ± 197,058	3.626 ± 0.197	1.400 ± 0.076
South Tahoma	STA	14	1,947,002 ± 108,888	1.947 ± 0.109	0.752 ± 0.042
Stevens[1]	STE	–	–	–	–
Success	SUC	23	396,133 ± 25,011	0.396 ± 0.025	0.153 ± 0.010
Tahoma	TAH	4	6,432,886 ± 342,616	6.433 ± 0.343	2.484 ± 0.132
Van Trump	VTR	28	116,854 ± 8,669	0.117 ± 0.009	0.045 ± 0.003
Whitman	WHI	15	1,845,758 ± 103,521	1.846 ± 0.104	0.713 ± 0.040
Wilson	WIL	17	1,459,495 ± 82,964	1.459 ± 0.083	0.564 ± 0.032
Winthrop	WIN	2	8,687,940 ± 458,769	8.688 ± 0.459	3.354 ± 0.177
Other Ice/Snow (total)	**OTH**	**–**	**1,938,117 ± 111,686**	**1.938 ± 0.112**	**0.748 ± 0.043**
Total (Excluding ice/snow):	**n/a**	**n/a**	**75,494,588 ± 4,109,073**	**75.496 ± 4.109**	**29.149 ± 1.587**
Total (all):	**n/a**	**n/a**	**77,433,706 ± 4,220,759**	**77.434 ± 4.221**	**29.897 ± 1.630**

[1] The extent of the former Stevens Glacier is now included in “Other Ice/Snow” since the glacier was removed from the Park’s inventory in 2021.

Glacier extent has changed remarkably during the six-year period between the 2015 study (Beason, 2017) and current snapshot. Almost all glacial boundaries have changed in some way and several of the south facing glaciers at Mount Rainier are becoming increasingly more fragmented, meaning ice has melted to the point that the formerly covered ground is now being exposed in large areas.

5.2. Glaciers Removed or Listed as Endangered in the 2021 Inventory

Glaciers are a "perennial mass of ice, and possibly firn and snow, originating on the land surface by the recrystallization of snow or other forms of solid precipitation and showing evidence of past or present flow" (Cogley et al., 2011). The definition does not specify a minimum size for a perennial snowfield to be named as a glacier. Fountain and others (2017), in their inventory of glaciers in the western US, suggest that around 0.01 km^2 (0.004 mi^2) the error of omission is roughly equal to commission. Further 0.01 km^2 (0.004 mi^2) seems to be the evolving international threshold for counting glaciers (Fountain et al., 2017).

While all glaciers at Mount Rainier are retreating, and – as the total volumetric change and mass change from 1896 to 2021 show – thinning, the glaciers on the south side of MORA are disappearing faster than glaciers on the north. Several of these glaciers are *rapidly* retreating, thinning, and fragmenting into multiple, smaller, individual pieces.

The conditions that have led to the formation of the Stevens Glacier include many factors that have placed it in a vulnerable state. It is a south-facing glacier that is an offshoot of the Paradise Glacier; the Paradise Glacier was already a feature that has had a rapid loss of glacial and ice due to the lower Paradise Glacier becoming cut off from its accumulation zone by bedrock topography. The famous former Paradise ice caves (which disappeared in the 1980s [NPS, 1989]) and the nearby Williwakas Glacier (which was noted in 1931 to be a "dead glacier" [NPS, 1931]) were the first cryospheric features that disappeared in the 20th century and a harbinger of things to come for glaciers in this area.

The Stevens Glacier in 2021 (Figure 4) showed no obvious evidence of movement (e.g., crevasses), had no connection to any larger glacial mass above it (providing future glacial ice accumulation to the system), and had an area of about 0.033 km^2 (8 acres) in 2015 and 0.029 km^2 (7 acres) in 2021. The feature is essentially a perennial snowfield. Therefore, we remove the Stevens Glacier from the Park's glacier inventory and reduce the total number of glaciers at Mount Rainier to 28.

Several other south-facing glaciers have lost massive amounts of area and mass in 2021 relative to 2015. While these glaciers are still showing some signs of movement, several have fragmented significantly. The two most at risk for future ice loss are the Pyramid and Van Trump glaciers. In the six-year period between 2015 and 2021, these two glaciers lost 32.9% and 33.6% of their area and 42.0% and 42.9% of their volume, respectively. These glaciers are "critically endangered" and should be carefully watched over the next decade to determine whether they are still meeting the definition of a glacier. On the north side of the Park and to a lesser extent, the Flett, Inter, and Sarvent glaciers are also at elevated risk for future loss. These three glaciers should be considered "endangered" and monitored over the next several decades.

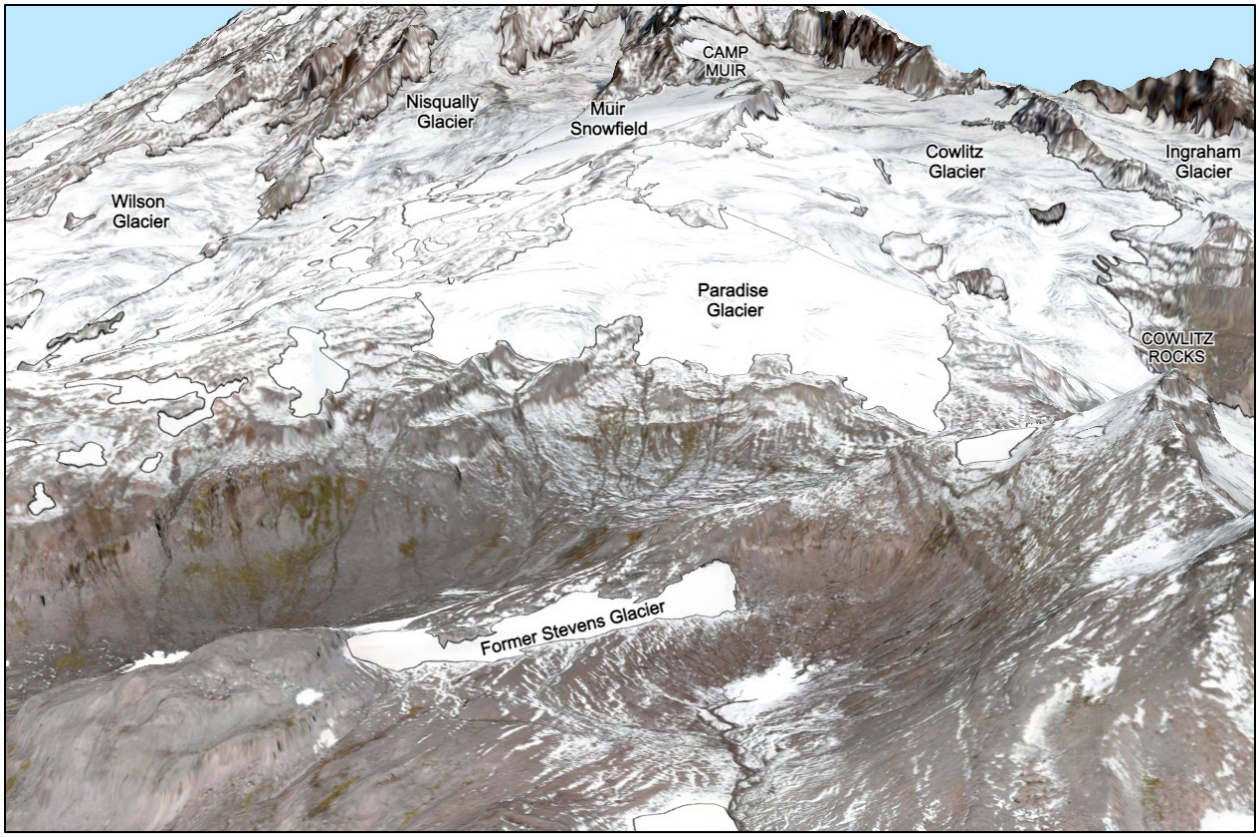


Figure 4. ESRI ArcGIS® Pro Scene generated oblique aerial image of the former Stevens Glacier and vicinity based on the 2021 SfM digital orthophoto and DSM.

From a hazard perspective, it should be noted that glaciers bind up loose and unconsolidated sediment on steep slopes that mantle the volcano. Both the Pyramid and Van Trump glaciers have been sources of debris flows in the November 2006 atmospheric river storm that dropped about 46 cm (18 in) of rain in 36 hours (Copeland, 2009). In prior decades, they have been sources of debris flows several times over the last two decades (Walder and Driedger, 1994). Without glacier ice, the unstable landscape surrounding former glaciers in the Park is prone to significant erosion and bank collapse, potentially creating increased debris flow activity. Mechanisms like these have been noted to initiate debris flows at Mount Rainier (Lancaster et al., 2012) and other Cascade Volcanoes (De La Fuente et al., 2015; Mikulovsky et al., 2015). These potential source locations at Mount Rainier are all upslope of significant tracts of Park infrastructure and introduce increasing risk to some of these locations.

5.3. Glacier Topography

The topographic characteristics of the glaciers are compiled in Table 5, which can be compared directly with the 2015 characteristics in Beason (2017, Table 8, Page 25) (Table 6). Glaciers occupy an elevation range between 1,102 m (3,617 ft) to 4,387 m (14,393 ft) on the mountain and vary from 0.48 km (0.30 mi) to 8.08 km (5.02 mi) in length. Additionally, glaciers have a slope that varies from 10° to 32°, averaging 24°.

Table 5. Topographic statistics of glaciers at Mount Rainier based on 2021 extent.

Glacier	Max. Elevation		Min. Elevation		Elevation Range		Length		Avg. Slope		Avg. Flow Dir
	m	ft	m	ft	m	ft	km	mi	°	°	
Carbon	3,722	12,212	1,102	3,617	2,620	8,594	8.08	5.02	20	353	N
Columbia Crest	4,387	14,393	4,312	14,146	76	248	0.68	0.43	10	96	E
Cowlitz	3,395	11,137	1,595	5,232	1,800	5,906	5.59	3.48	23	121	ESE
Edmunds	3,080	10,105	2,121	6,958	959	3,147	2.04	1.27	24	287	WNW
Emmons	4,312	14,148	1,488	4,883	2,824	9,266	7.32	4.55	24	55	NE
Flett	2,423	7,951	2,170	7,120	253	831	0.66	0.41	20	356	N
Fryingpan	3,027	9,930	2,162	7,093	865	2,838	1.59	0.98	22	38	NE
Ingraham	4,287	14,064	1,979	6,493	2,308	7,572	5.18	3.22	25	120	ESE
Inter	2,934	9,627	2,248	7,376	686	2,251	1.48	0.92	26	25	NNE
Kautz	4,307	14,131	2,108	6,917	2,199	7,213	4.17	2.59	29	193	SSW
Liberty Cap	4,294	14,088	3,220	10,565	1,074	3,523	2.71	1.69	29	233	SW
Muir	3,071	10,077	2,505	8,219	566	1,858	1.89	1.18	18	183	S
Nisqually	4,380	14,371	1,630	5,347	2,751	9,024	5.74	3.57	27	166	SSE
North Mowich	3,715	12,189	1,655	5,429	2,060	6,760	4.12	2.56	25	322	NW
Ohanapecosh	2,558	8,392	2,210	7,250	348	1,141	0.79	0.49	21	72	ENE
Paradise	2,568	8,425	2,088	6,850	480	1,575	0.65	0.41	24	124	ESE
Puyallup	2,926	9,600	1,678	5,506	1,248	4,093	3.98	2.47	20	280	W
Pyramid	2,707	8,881	2,339	7,673	368	1,207	0.95	0.59	23	185	S
Russell	2,949	9,675	2,031	6,663	918	3,013	2.74	1.70	22	28	NNE
Sarvent	2,226	7,304	1,839	6,033	387	1,271	0.58	0.36	32	30	NNE
South Mowich	3,913	12,839	1,493	4,897	2,421	7,942	6.08	3.78	26	272	W
South Tahoma	3,295	10,811	2,019	6,625	1,276	4,186	3.22	2.00	24	219	SW
Stevens	–	–	–	–	–	–	–	–	–	–	–
Success	3,239	10,625	2,584	8,477	655	2,148	1.19	0.74	29	184	S

Table 5 (continued). Topographic statistics of glaciers at Mount Rainier based on 2021 extent.

Glacier	Max. Elevation		Min. Elevation		Elevation Range		Length		Avg. Slope		Avg. Flow Dir
	m	ft	m	ft	m	ft	km	mi	°	°	
Tahoma	4,369	14,334	1,679	5,510	2,690	8,824	6.44	4.00	24	243	WSW
Van Trump	2,622	8,602	2,298	7,540	324	1,063	0.48	0.30	28	168	SSE
Whitman	3,135	10,286	2,310	7,579	825	2,707	3.25	2.02	16	142	SE
Wilson	3,292	10,801	2,053	6,735	1,239	4,066	2.11	1.31	26	142	SE
Winthrop	4,360	14,305	1,479	4,852	2,882	9,454	7.83	4.86	24	20	NNE
Minimum:	**2,031**	**6,663**	**1,102**	**3,617**	**76**	**248**	**0.48**	**0.30**	**10**	n/a	n/a
Average:	**3,378**	**11,082**	**2,118**	**6,950**	**1,325**	**4,347**	**3.27**	**2.03**	**24**	n/a	n/a
Maximum:	**4,387**	**14,393**	**4,312**	**14,146**	**2,882**	**9,454**	**8.08**	**5.02**	**32**	n/a	n/a

Table 6. Comparison of glacier statistics between 2015 and 2021 (2015 data is based on Table 8 in Beason, 2017, Page 25). A positive change in this table means the metric increased from 2015 to 2021 (e.g., a positive minimum elevation means the minimum elevation of the glacier moved upwards in 2021 relative to 2015).

Glacier	Maximum Elevation (m)	Minimum Elevation (m)	Elevation Range (m)	Length (km)	Slope (deg)	Flow Direction (deg)
Carbon	-23	20	-44	-0.32	-5	8
Columbia Crest	-5	0	-6	0.00	-1	-16
Cowlitz	-10	-15	5	-0.23	-2	0
Edmunds	-8	-6	-1	-0.08	-2	8
Emmons	-8	-3	-5	-0.35	-6	7
Flett	-8	55	-63	-0.07	0	4
Fryingpan	-3	-21	18	-0.39	-2	4
Ingraham	-5	-7	2	0.00	-6	-3
Inter	0	13	-14	0.00	0	10
Kautz	-6	38	-44	-0.09	-6	-6
Liberty Cap	-10	-6	-4	0.00	-1	-81
Muir	-5	23	-28	-0.02	0	-2
Nisqually	-8	15	-23	-0.44	-3	-8
N. Mowich	-2	21	-23	-0.35	-3	6
Ohanapecosh	-41	54	-94	-0.07	-1	0
Paradise	-16	-12	-4	-0.10	1	-6
Puyallup	-196	-8	-188	-0.31	-2	2
Pyramid	-258	66	-325	-0.28	2	-3
Russell	-29	-13	-17	-0.06	-1	9
Sarvent	32	-19	51	-0.18	7	24
S. Mowich	-11	-39	27	-0.05	-7	0
S. Tahoma	-4	-18	14	-0.07	-5	-7
Stevens	-8	31	-40	-0.48	0	9
Success	15	14	1	0.00	-2	-8
Tahoma	-4	-197	192	-0.59	-5	-7
Van Trump	-193	97	-290	-0.94	2	-8
Whitman	-4	-1	-3	0.00	-1	-6
Wilson	-11	21	-32	0.00	-4	-6
Winthrop	-22	3	-26	-0.21	-4	7
Minimum:	**-258**	**-197**	**-325**	**-0.94**	**-7**	**-81**
Average:	**-29**	**4**	**-33**	**-0.20**	**-2**	**-2**
Maximum:	**32**	**97**	**192**	**0.00**	**7**	**24**
Total:	**n/a**	**n/a**	**n/a**	**-5.67**	**n/a**	**n/a**

Some glaciers had multiple mapped features (multipart polygons). 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 the features.

Distinct from other glaciers on Mount Rainier, the Columbia Crest Glacier (Figure 5) is situated in and between the east and west rims of the volcano, which restricts outward flow. Consequently, some of the statistics of the glacier may appear to be unreasonable.

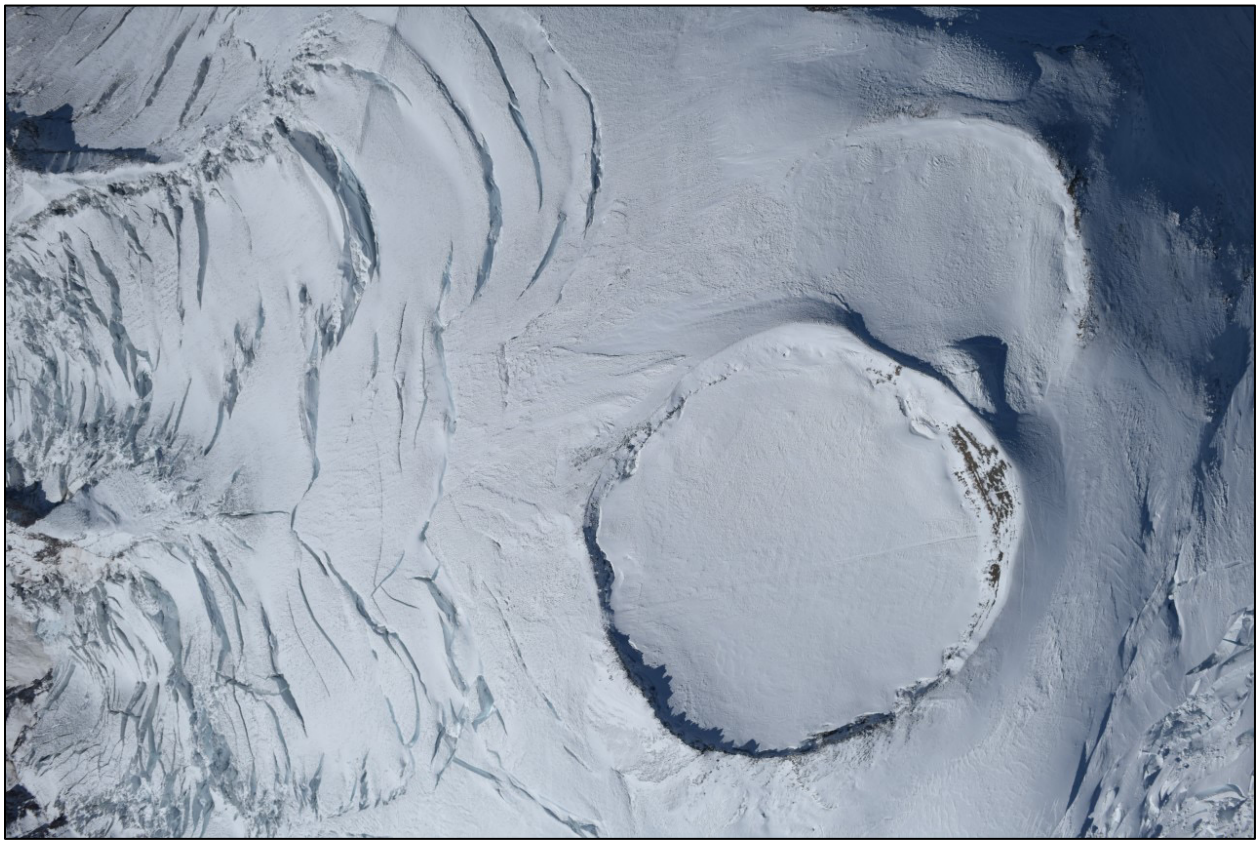


Figure 5. Photo of the Mount Rainier summit and vicinity showing the circular bowl that contains the Columbia Crest Glacier from the 21 September 2021 SfM flight. North is to the lower right in this photo.

The average maximum elevation of glaciers in the Park decreased by -29 m (-95 ft) (ranging from -258 to 32 m [-846 to 105 ft]), meaning that the elevation at the head of the average glacier in the Park decreased (Table 6). The average minimum elevation of glaciers at the Park increased by 4 m (-13 ft) (ranging from -197 to 97 m [-646 to 318 ft]), meaning that the elevation at the terminus of the average glacier in the Park increased. Accordingly, the elevation range of the average glacier in the Park went down by -33 m (-108 ft) (ranging from -325 to 192 m [-1,066 to 630 ft]), meaning the average glacier at Mount Rainier now occupies a smaller elevation range.

The average length of glaciers at Mount Rainier has decreased by -0.20 km (-0.12 mi) (ranging from -0.94 to 0 km [-0.58 to 0 mi]), meaning that the average glacier's total length has decreased (Table

6). When looking at the total length of all glaciers at MORA (i.e., the sum of the lengths of all glaciers in the Park), the Park has lost -5.67 km (-3.52 mi) of glacial length (88.33 km [54.89 mi] in 2015 and 82.66 km [51.36 mi] in 2021).

The average slope of glaciers at Mount Rainier has decreased by -2 degrees (ranging from -7 to 7 degrees), meaning the average glacier at Mount Rainier has become less steep (Table 6). The average flow direction of glaciers at Mount Rainier has changed by about -2 degrees (ranging from -81 to 24 degrees) (Table 6). The biggest changes have occurred on the Liberty Cap, Columbia Crest (which has no outlet), and Sarvent Glaciers at the Park, and is likely due to complex snow surface patterns on these glaciers. All other glaciers had an average flow direction change of ± 10 degrees, which is negligible.

5.4. Glacial Area Change – 1896 to 2021

To define changes in glacial area at Mount Rainier, the 2021 inventory was compared to prior glacial inventories in 1896, 1913, 1971, 1994, 2009, and 2015. Figure 6 and Table 7 show the comparison of the 2021 inventory with the previous inventories. Table 8 shows the total area change in extent between inventories and Table 9 shows the total percentage change in extent between inventories.

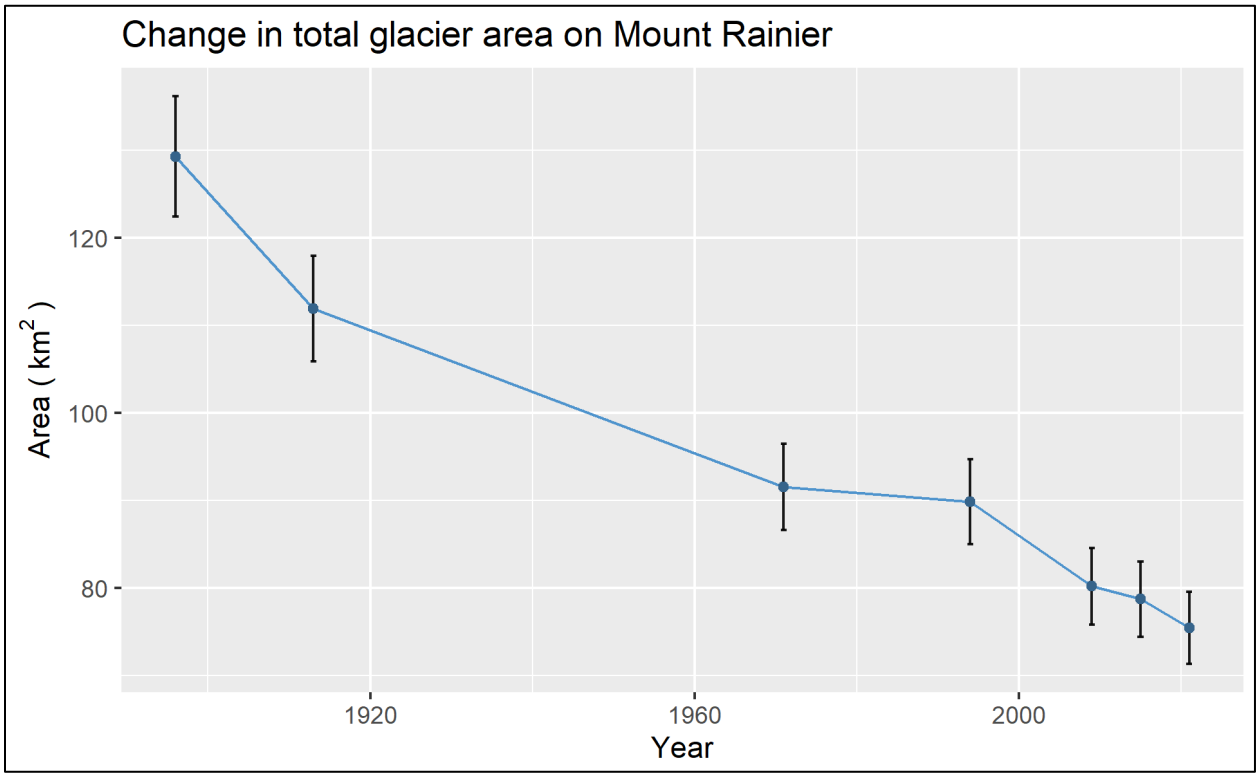


Figure 6. Overall change in total glacier area at Mount Rainier from 1896-2021, based on data in Table 7.

Table 7. Comparison of extents of individual 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	2021
Carbon	8.290 ± 0.438	8.455 ± 0.447	8.014 ± 0.424	7.976 ± 0.422	7.454 ± 0.395	7.257 ± 0.385	7.127 ± 0.378
Columbia Crest	0.322 ± 0.021	0.107 ± 0.008	0.251 ± 0.017	0.198 ± 0.014	0.118 ± 0.009	0.180 ± 0.013	0.172 ± 0.012
Cowlitz-Ingraham	8.310 ± 0.439	9.838 ± 0.518	7.639 ± 0.405	7.697 ± 0.408	7.048 ± 0.374	6.998 ± 0.381	6.647 ± 0.362
Edmunds	2.820 ± 0.155	1.530 ± 0.087	1.474 ± 0.084	1.417 ± 0.081	1.300 ± 0.074	1.252 ± 0.072	1.165 ± 0.067
Emmons	17.458 ± 0.907	12.622 ± 0.660	11.158 ± 0.586	11.223 ± 0.589	10.979 ± 0.576	11.027 ± 0.579	10.959 ± 0.575
Flett	–	0.737 ± 0.044	0.576 ± 0.035	0.615 ± 0.037	0.582 ± 0.035	0.406 ± 0.026	0.363 ± 0.023
Fryingpan	3.722 ± 0.202	6.121 ± 0.326	4.339 ± 0.234	4.231 ± 0.229	3.297 ± 0.180	3.245 ± 0.177	2.993 ± 0.164
Inter	0.570 ± 0.035	1.143 ± 0.066	0.836 ± 0.049	0.826 ± 0.049	0.665 ± 0.040	0.574 ± 0.035	0.532 ± 0.033
Kautz-Success	5.174 ± 0.278	3.028 ± 0.171	2.728 ± 0.155	2.201 ± 0.127	2.125 ± 0.118	2.081 ± 0.120	1.957 ± 0.113
Liberty Cap	2.822 ± 0.155	2.401 ± 0.133	2.079 ± 0.116	2.102 ± 0.117	2.200 ± 0.122	2.139 ± 0.119	2.076 ± 0.116
Muir	1.132 ± 0.065	1.216 ± 0.070	0.968 ± 0.057	0.977 ± 0.057	0.920 ± 0.054	0.875 ± 0.051	0.823 ± 0.049
Nisqually-Wilson	10.026 ± 0.527	6.588 ± 0.351	6.072 ± 0.324	6.254 ± 0.333	6.003 ± 0.320	5.754 ± 0.315	5.562 ± 0.305
North Mowich	11.074 ± 0.581	8.032 ± 0.425	6.261 ± 0.334	6.108 ± 0.326	5.207 ± 0.279	5.144 ± 0.276	4.907 ± 0.264
Ohanapecosh	–	2.968 ± 0.163	1.369 ± 0.078	1.389 ± 0.079	0.786 ± 0.047	0.669 ± 0.040	0.616 ± 0.037
Paradise-Stevens	4.863 ± 0.261	3.186 ± 0.174	1.364 ± 0.078	1.338 ± 0.076	0.778 ± 0.048	0.645 ± 0.040	0.581 ± 0.035
Puyallup	8.463 ± 0.447	5.213 ± 0.280	4.316 ± 0.233	4.348 ± 0.235	3.519 ± 0.191	3.258 ± 0.178	3.098 ± 0.169
Pyramid	2.747 ± 0.151	1.394 ± 0.079	0.710 ± 0.042	0.645 ± 0.039	0.379 ± 0.024	0.262 ± 0.017	0.176 ± 0.012
Russell	6.605 ± 0.352	4.909 ± 0.264	3.574 ± 0.194	3.637 ± 0.198	2.789 ± 0.153	2.892 ± 0.159	2.706 ± 0.149
Sarvent	–	1.148 ± 0.068	0.686 ± 0.042	0.146 ± 0.011	0.695 ± 0.043	0.455 ± 0.029	0.380 ± 0.025
South Mowich	5.331 ± 0.286	4.700 ± 0.253	4.091 ± 0.221	4.061 ± 0.220	3.963 ± 0.215	3.766 ± 0.204	3.626 ± 0.197
South Tahoma	5.926 ± 0.316	3.427 ± 0.187	2.922 ± 0.160	2.233 ± 0.124	2.206 ± 0.123	2.002 ± 0.112	1.947 ± 0.109
Tahoma	12.005 ± 0.629	9.171 ± 0.484	7.619 ± 0.404	7.281 ± 0.386	6.777 ± 0.360	6.787 ± 0.361	6.433 ± 0.343
Van Trump	1.438 ± 0.082	1.402 ± 0.080	0.681 ± 0.041	0.724 ± 0.043	0.318 ± 0.021	0.176 ± 0.012	0.117 ± 0.009
Whitman	1.974 ± 0.110	2.432 ± 0.134	2.226 ± 0.124	2.315 ± 0.128	2.101 ± 0.117	1.939 ± 0.108	1.846 ± 0.104

Table 7 (continued). Comparison of extents of individual 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	2021
Winthrop	8.235 ± 0.435	10.183 ± 0.536	9.631 ± 0.507	9.943 ± 0.523	8.015 ± 0.424	8.977 ± 0.474	8.688 ± 0.459
Total:	**129.308 ± 6.874**	**111.950 ± 6.006**	**91.583 ± 4.944**	**89.882 ± 4.851**	**80.222 ± 4.344**	**78.758 ± 4.283**	**75.496 ± 4.109**

Table 8. Total 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 ($km^2 \times yr^{-1}$).

Glacier Name	1896–1913	1896–1971	1896–1994	1896–2009	1896–2015	1896–2021	1913–1971	1913–1994	1913–2009	1913–2015	1913–2021	1971–1994	1971–2009	1971–2015	1971–2021	1994–2009	1994–2015	1994–2021	2009–2015	2009–2021	2015–2021
Carbon	0.17	-0.28	-0.31	-0.84	-1.03	-1.16	-0.44	-0.48	-1.00	-1.20	-1.33	-0.04	-0.56	-0.76	-0.89	-0.52	-0.72	-0.85	-0.20	-0.33	-0.13
Columbia Crest	-0.21	-0.07	-0.12	-0.20	-0.14	-0.15	0.14	0.09	0.01	0.07	0.07	-0.05	-0.13	-0.07	-0.08	-0.08	-0.02	-0.03	0.06	0.05	-0.01
Cowlitz-Ingraham	1.53	-0.67	-0.61	-1.26	-1.31	-1.66	-2.20	-2.14	-2.79	-2.84	-3.19	0.06	-0.59	-0.64	-0.99	-0.65	-0.70	-1.05	-0.05	-0.40	-0.35
Edmunds	-1.29	-1.35	-1.40	-1.52	-1.57	-1.66	-0.06	-0.11	-0.23	-0.28	-0.37	-0.06	-0.17	-0.22	-0.31	-0.12	-0.16	-0.25	-0.05	-0.14	-0.09
Emmons	-4.84	-6.30	-6.24	-6.48	-6.43	-6.50	-1.46	-1.40	-1.64	-1.60	-1.66	0.06	-0.18	-0.13	-0.20	-0.24	-0.20	-0.26	0.05	-0.02	-0.07
Flett	–	–	–	–	–	–	-0.16	-0.12	-0.15	-0.33	-0.37	0.04	0.01	-0.17	-0.21	-0.03	-0.21	-0.25	-0.18	-0.22	-0.04
Fryingpan	2.40	0.62	0.51	-0.43	-0.48	-0.73	-1.78	-1.89	-2.82	-2.88	-3.13	-0.11	-1.04	-1.09	-1.35	-0.93	-0.99	-1.24	-0.05	-0.30	-0.25
Inter	0.57	0.27	0.26	0.10	0.00	-0.04	-0.31	-0.32	-0.48	-0.57	-0.61	-0.01	-0.17	-0.26	-0.30	-0.16	-0.25	-0.29	-0.09	-0.13	-0.04
Kautz-Success	-2.15	-2.45	-2.97	-3.05	-3.09	-3.22	-0.30	-0.83	-0.90	-0.95	-1.07	-0.53	-0.60	-0.65	-0.77	-0.08	-0.12	-0.24	-0.04	-0.17	-0.12
Liberty Cap	-0.42	-0.74	-0.72	-0.62	-0.68	-0.75	-0.32	-0.30	-0.20	-0.26	-0.33	0.02	0.12	0.06	0.00	0.10	0.04	-0.03	-0.06	-0.12	-0.06
Muir	0.08	-0.16	-0.16	-0.21	-0.26	-0.31	-0.25	-0.24	-0.30	-0.34	-0.39	0.01	-0.05	-0.09	-0.15	-0.06	-0.10	-0.15	-0.04	-0.10	-0.05
Nisqually-Wilson	-3.44	-3.95	-3.77	-4.02	-4.27	-4.46	-0.52	-0.33	-0.59	-0.83	-1.03	0.18	-0.07	-0.32	-0.51	-0.25	-0.50	-0.69	-0.25	-0.44	-0.19
North Mowich	-3.04	-4.81	-4.97	-5.87	-5.93	-6.17	-1.77	-1.92	-2.83	-2.89	-3.13	-0.15	-1.05	-1.12	-1.35	-0.90	-0.96	-1.20	-0.06	-0.30	-0.24
Ohanapecosh	–	–	–	–	–	–	-1.60	-1.58	-2.18	-2.30	-2.35	0.02	-0.58	-0.70	-0.75	-0.60	-0.72	-0.77	-0.12	-0.17	-0.05
Paradise-Stevens	-1.68	-3.50	-3.53	-4.09	-4.22	-4.28	-1.82	-1.85	-2.41	-2.54	-2.61	-0.03	-0.59	-0.72	-0.78	-0.56	-0.69	-0.76	-0.13	-0.20	-0.06
Puyallup	-3.25	-4.15	-4.12	-4.94	-5.21	-5.37	-0.90	-0.86	-1.69	-1.95	-2.12	0.03	-0.80	-1.06	-1.22	-0.83	-1.09	-1.25	-0.26	-0.42	-0.16
Pyramid	-1.35	-2.04	-2.10	-2.37	-2.48	-2.57	-0.68	-0.75	-1.02	-1.13	-1.22	-0.06	-0.33	-0.45	-0.53	-0.27	-0.38	-0.47	-0.12	-0.20	-0.09
Russell	-1.70	-3.03	-2.97	-3.82	-3.71	-3.90	-1.33	-1.27	-2.12	-2.02	-2.20	0.06	-0.78	-0.68	-0.87	-0.85	-0.74	-0.93	0.10	-0.08	-0.19
Sarvent	–	–	–	–	–	–	-0.46	-1.00	-0.45	-0.69	-0.77	-0.54	0.01	-0.23	-0.31	0.55	0.31	0.23	-0.24	-0.31	-0.07
South Mowich	-0.63	-1.24	-1.27	-1.37	-1.57	-1.70	-0.61	-0.64	-0.74	-0.93	-1.07	-0.03	-0.13	-0.33	-0.46	-0.10	-0.30	-0.43	-0.20	-0.34	-0.14
South Tahoma	-2.50	-3.00	-3.69	-3.72	-3.92	-3.98	-0.51	-1.19	-1.22	-1.43	-1.48	-0.69	-0.72	-0.92	-0.97	-0.03	-0.23	-0.29	-0.20	-0.26	-0.05
Tahoma	-2.83	-4.39	-4.72	-5.23	-5.22	-5.57	-1.55	-1.89	-2.39	-2.38	-2.74	-0.34	-0.84	-0.83	-1.19	-0.50	-0.49	-0.85	0.01	-0.34	-0.35
Van Trump	-0.04	-0.76	-0.71	-1.12	-1.26	-1.32	-0.72	-0.68	-1.08	-1.23	-1.29	0.04	-0.36	-0.51	-0.56	-0.41	-0.55	-0.61	-0.14	-0.20	-0.06
Whitman	0.46	0.25	0.34	0.13	-0.04	-0.13	-0.21	-0.12	-0.33	-0.49	-0.59	0.09	-0.12	-0.29	-0.38	-0.21	-0.38	-0.47	-0.16	-0.26	-0.09
Winthrop	1.95	1.40	1.71	-0.22	0.74	0.45	-0.55	-0.24	-2.17	-1.21	-1.50	0.31	-1.62	-0.65	-0.94	-1.93	-0.97	-1.26	0.96	0.67	-0.29
Total Change:	**-22.21**	**-40.36**	**-41.58**	**-51.15**	**-52.08**	**-55.17**	**-20.37**	**-22.07**	**-31.73**	**-33.19**	**-36.45**	**-1.70**	**-11.36**	**-12.82**	**-16.09**	**-9.66**	**-11.12**	**-14.39**	**-1.46**	**-4.73**	**-3.26**
Years:	**17**	**75**	**98**	**113**	**119**	**125**	**58**	**81**	**96**	**102**	**108**	**23**	**38**	**44**	**50**	**15**	**21**	**27**	**6**	**12**	**6**
Avg. Change:	**-1.31**	**-0.54**	**-0.42**	**-0.45**	**-0.44**	**-0.44**	**-0.35**	**-0.27**	**-0.33**	**-0.33**	**-0.34**	**-0.07**	**-0.30**	**-0.29**	**-0.32**	**-0.64**	**-0.53**	**-0.53**	**-0.24**	**-0.39**	**-0.54**

Table 9. 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}).

Glacier Name	1896–1913	1896–1971	1896–1994	1896–2009	1896–2015	1896–2021	1913–1971	1913–1994	1913–2009	1913–2015	1913–2021	1971–1994	1971–2009	1971–2015	1971–2021	1994–2009	1994–2015	1994–2021	2009–2015	2009–2021	2015–2021
Carbon	2.0	-3.3	-3.8	-10.1	-12.5	-14.0	-5.2	-5.7	-11.8	-14.2	-15.7	-0.5	-7.0	-9.4	-11.1	-6.5	-9.0	-10.6	-2.7	-4.4	-1.8
Columbia Crest	-66.8	-22.1	-38.6	-63.4	-43.9	-46.5	134.6	84.9	10.4	68.8	61.2	-21.2	-53.0	-28.0	-31.3	-40.3	-8.7	-12.8	53.0	46.1	-4.5
Cowlitz-Ingraham	18.4	-8.1	-7.4	-15.2	-15.8	-20.0	-22.3	-21.8	-28.4	-28.9	-32.4	0.8	-7.7	-8.4	-13.0	-8.4	-9.1	-13.6	-0.7	-5.7	-5.0
Edmunds	-45.7	-47.7	-49.8	-53.9	-55.6	-58.7	-3.7	-7.4	-15.0	-18.1	-23.9	-3.9	-11.8	-15.0	-21.0	-8.2	-11.6	-17.8	-3.7	-10.4	-7.0
Emmons	-27.7	-36.1	-35.7	-37.1	-36.8	-37.2	-11.6	-11.1	-13.0	-12.6	-13.2	0.6	-1.6	-1.2	-1.8	-2.2	-1.7	-2.3	0.4	-0.2	-0.6
Flett	–	–	–	–	–	–	-21.7	-16.5	-21.0	-44.9	-50.7	6.8	1.0	-29.6	-37.0	-5.4	-34.1	-41.0	-30.3	-37.6	-10.5
Fryingpan	64.5	16.6	13.7	-11.4	-12.8	-19.6	-29.1	-30.9	-46.1	-47.0	-51.1	-2.5	-24.0	-25.2	-31.0	-22.1	-23.3	-29.3	-1.6	-9.2	-7.7
Inter	100.5	46.6	44.8	16.7	0.7	-6.6	-26.9	-27.8	-41.8	-49.8	-53.4	-1.2	-20.4	-31.3	-36.3	-19.4	-30.5	-35.5	-13.7	-20.0	-7.2
Kautz-Success	-41.5	-47.3	-57.5	-58.9	-59.8	-62.2	-9.9	-27.3	-29.8	-31.3	-35.4	-19.3	-22.1	-23.7	-28.3	-3.4	-5.5	-11.1	-2.1	-7.9	-5.9
Liberty Cap	-14.9	-26.3	-25.5	-22.1	-24.2	-26.5	-13.4	-12.4	-8.4	-10.9	-13.5	1.1	5.8	2.9	-0.2	4.7	1.8	-1.2	-2.8	-5.6	-2.9
Muir	7.4	-14.5	-13.7	-18.7	-22.7	-27.3	-20.4	-19.7	-24.3	-28.0	-32.3	0.9	-5.0	-9.6	-15.0	-5.8	-10.4	-15.8	-4.9	-10.6	-6.0
Nisqually-Wilson	-34.3	-39.4	-37.6	-40.1	-42.6	-44.5	-7.8	-5.1	-8.9	-12.7	-15.6	3.0	-1.1	-5.2	-8.4	-4.0	-8.0	-11.1	-4.2	-7.4	-3.3
North Mowich	-27.5	-43.5	-44.8	-53.0	-53.5	-55.7	-22.1	-24.0	-35.2	-36.0	-38.9	-2.4	-16.8	-17.8	-21.6	-14.8	-15.8	-19.7	-1.2	-5.8	-4.6
Ohanapecosh	–	–	–	–	–	–	-53.9	-53.2	-73.5	-77.5	-79.3	1.4	-42.6	-51.2	-55.0	-43.4	-51.8	-55.7	-14.8	-21.6	-8.0
Paradise-Stevens	-34.5	-72.0	-72.5	-84.0	-86.7	-88.1	-57.2	-58.0	-75.6	-79.8	-81.8	-1.9	-43.0	-52.7	-57.4	-41.9	-51.8	-56.6	-17.1	-25.4	-10.0
Puyallup	-38.4	-49.0	-48.6	-58.4	-61.5	-63.4	-17.2	-16.6	-32.5	-37.5	-40.6	0.7	-18.5	-24.5	-28.2	-19.1	-25.1	-28.8	-7.4	-12.0	-4.9
Pyramid	-49.2	-74.2	-76.5	-86.2	-90.5	-93.6	-49.1	-53.7	-72.8	-81.2	-87.4	-9.1	-46.6	-63.0	-75.2	-41.3	-59.3	-72.7	-30.7	-53.5	-32.9
Russell	-25.7	-45.9	-44.9	-57.8	-56.2	-59.0	-27.2	-25.9	-43.2	-41.1	-44.9	1.8	-22.0	-19.1	-24.3	-23.3	-20.5	-25.6	3.7	-3.0	-6.5
Sarvent	–	–	–	–	–	–	-40.2	-87.3	-39.4	-60.4	-66.8	-78.8	1.3	-33.7	-44.6	377.0	212.1	161.1	-34.6	-45.3	-16.3
South Mowich	-11.8	-23.3	-23.8	-25.7	-29.4	-32.0	-13.0	-13.6	-15.7	-19.9	-22.8	-0.7	-3.1	-8.0	-11.4	-2.4	-7.3	-10.7	-5.0	-8.5	-3.7
South Tahoma	-42.2	-50.7	-62.3	-62.8	-66.2	-67.1	-14.8	-34.9	-35.6	-41.6	-43.2	-23.6	-24.5	-31.5	-33.4	-1.2	-10.3	-12.8	-9.3	-11.7	-2.7
Tahoma	-23.6	-36.5	-39.4	-43.5	-43.5	-46.4	-16.9	-20.6	-26.1	-26.0	-29.9	-4.4	-11.1	-10.9	-15.6	-6.9	-6.8	-11.6	0.2	-5.1	-5.2
Van Trump	-2.5	-52.6	-49.6	-77.9	-87.8	-91.9	-51.4	-48.3	-77.3	-87.5	-91.7	6.3	-53.4	-74.2	-82.8	-56.2	-75.7	-83.9	-44.6	-63.2	-33.6
Whitman	23.2	12.7	17.3	6.4	-1.8	-6.5	-8.5	-4.8	-13.6	-20.3	-24.1	4.0	-5.6	-12.9	-17.1	-9.2	-16.3	-20.3	-7.7	-12.2	-4.8
Winthrop	23.7	17.0	20.8	-2.7	9.0	5.5	-5.4	-2.4	-21.3	-11.8	-14.7	3.2	-16.8	-6.8	-9.8	-19.4	-9.7	-12.6	12.0	8.4	-3.2
Total Change:	**-13.4**	**-29.2**	**-30.5**	**-38.0**	**-39.1**	**-41.6**	**-18.2**	**-19.7**	**-28.3**	**-29.6**	**-32.6**	**-1.9**	**-12.4**	**-14.0**	**-17.6**	**-10.7**	**-12.4**	**-16.0**	**-1.8**	**-5.9**	**-4.1**
Years:	**17**	**75**	**98**	**113**	**119**	**125**	**58**	**81**	**96**	**102**	**108**	**23**	**38**	**44**	**50**	**15**	**21**	**27**	**6**	**12**	**6**
Avg. Change:	**-0.79**	**-0.39**	**-0.31**	**-0.34**	**-0.33**	**-0.33**	**-0.31**	**-0.24**	**-0.30**	**-0.29**	**-0.30**	**-0.08**	**-0.33**	**-0.32**	**-0.35**	**-0.72**	**-0.59**	**-0.59**	**-0.30**	**-0.49**	**-0.69**

Area changes of each glacier is instructive to show that they all do not vary identically (Figures 7-9). Figure 7 shows the changes in glacial area for those glaciers and glacial systems (e.g., Nisqually and

Wilson Glaciers together) whose 2021 surface area is greater than (or near) 5 km^2 (1.9 mi^2). It should be noted that the North Mowich Glacier has an extent less than 5 km^2; it is included in Figure 7 to be consistent with a similar figure in Beason (2017). Figure 8 shows glaciers and glacial systems whose area is between 1 – 5 km^2 (0.4 – 1.9 mi^2) and Figure 9 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 2021 and associated data are included in Appendix B.

The total loss of glacial area between 1896 and 2021 was -55.33 km^2 (-21.36 mi^2) (Figure 6, Table 8). All time periods showed loss of glacial area; however, the period between 1896 and 1913 had the fastest rate of area decrease (-1.31 $km^2 \times yr^{-1}$ [-0.50 $mi^2 \times yr^{-1}$]). The period between 1994 and 2009 had the second fastest rate of surface area decrease (-0.64 $km^2 \times yr^{-1}$ [-0.25 $mi^2 \times yr^{-1}$]) and the most recent period between 2015 and 2021 had a surface area decrease of -0.54 $km^2 \times yr^{-1}$ (-0.21 $mi^2 \times yr^{-1}$). 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). Additionally, a rock avalanche onto the upper Emmons Glacier is thought to have caused an advance due to the insulating properties of the rock that reduced snow and ice ablation (Crandell and Fahnestock, 1965).

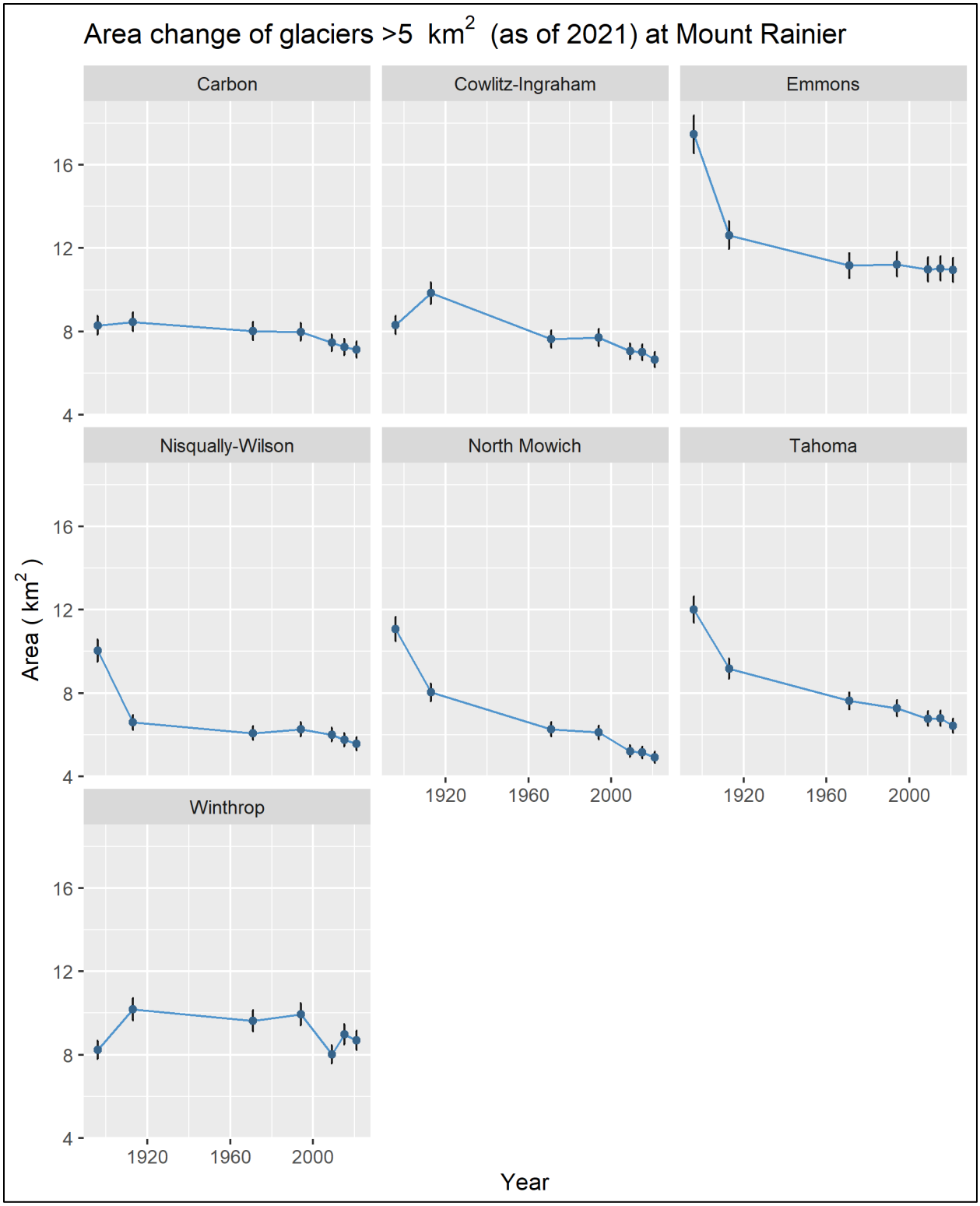


Figure 7. Change in surface area of glaciers from 1896 to 2021 that had a 2021 extent greater than or near five square kilometers, based on data in Table 7. North Mowich glacier included here to be consistent with a similar figure in Beason (2017).

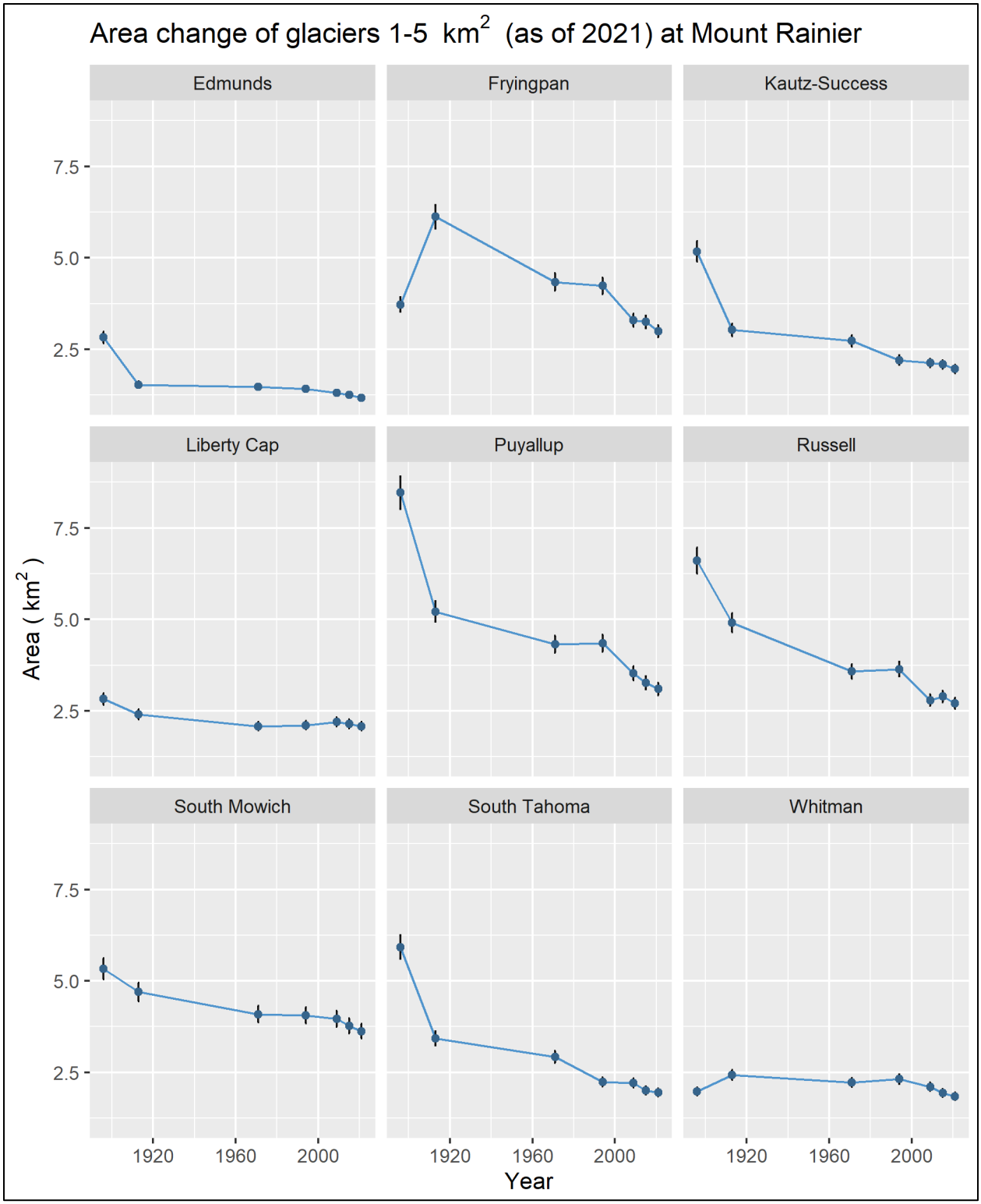


Figure 8. Change in surface area of glaciers from 1896 to 2021 that had a 2021 extent between 1 and 5 square kilometers, based on data in Table 7.

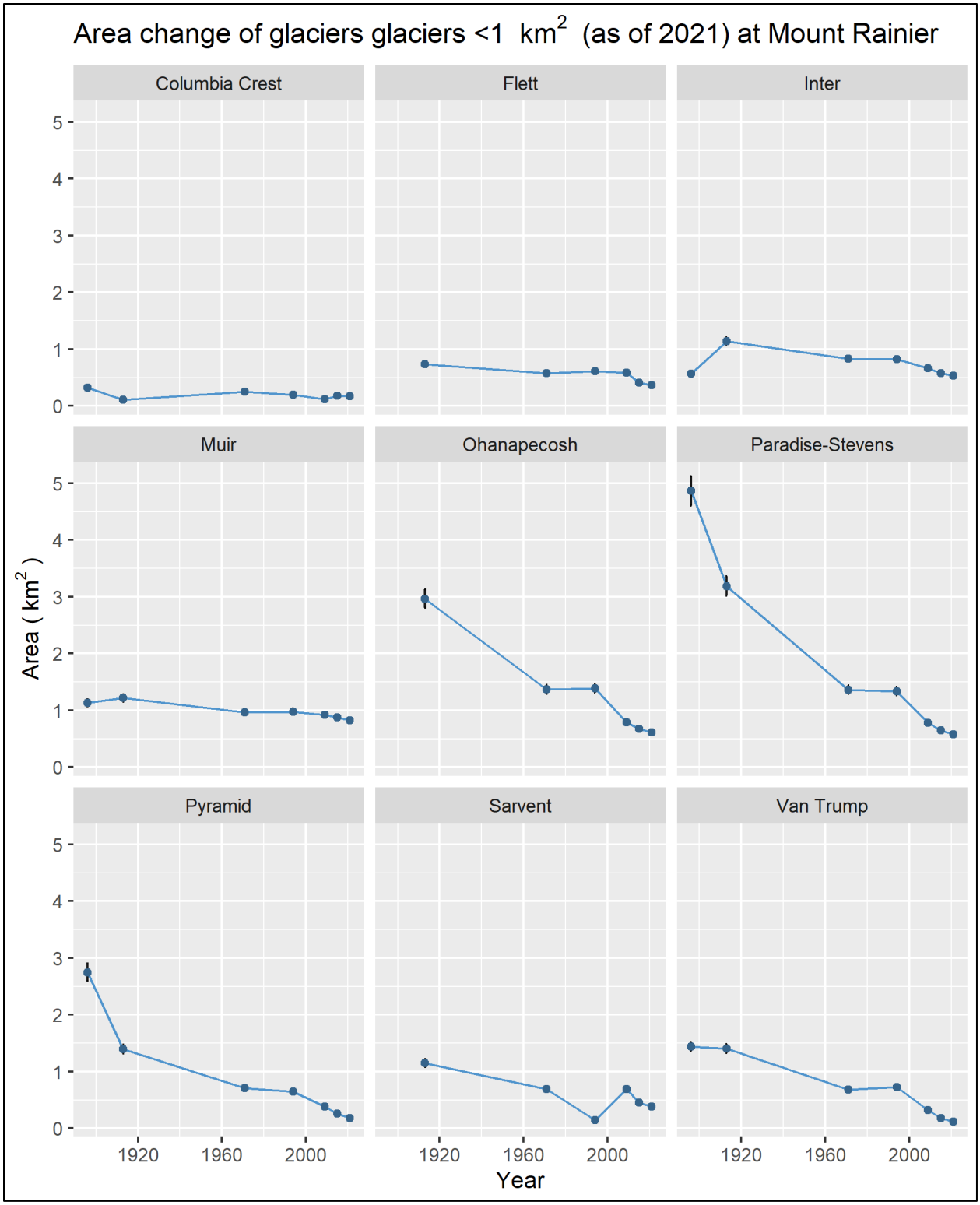


Figure 9. Change in surface area of glaciers from 1896 to 2021 that had a 2021 extent less than 1 square kilometer, based on data in Table 7.

To evaluate whether changes in surface area are sensitive to the direction they face and hence solar energy, they were divided into two groups: north and south facing (Figure 10 and Table 10). For the purposes of this study, the north-facing glaciers (11) include the Carbon, Edmunds, Emmons, Flett, Fryingpan, Inter, Liberty Cap, North Mowich, Russell, Sarvent, and Winthrop glaciers; while the south-facing glaciers (18) 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.

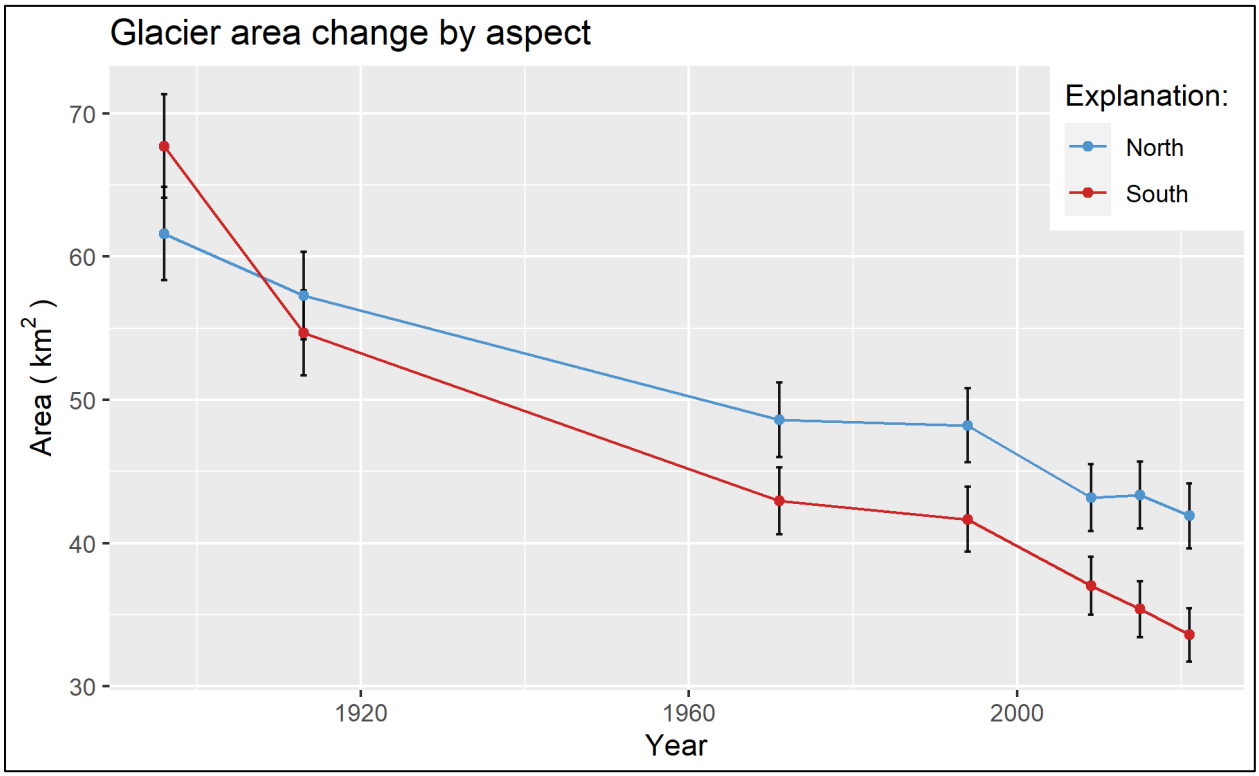


Figure 10. Glacier area change by aspect from 1896 to 2021 at Mount Rainier, based on data from Table 10.

Table 10. Glacier area change by aspect at Mount Rainier for various time periods. Listed units are in square kilometers (km^2)

Aspect	1896	1913	1971	1994	2009	2015	2021	1896–2021 Change	1896–2021 Change (%)
North[1]	61.59	57.28	48.63	48.22	43.18	43.37	41.90	-19.70	-32.0
South[1]	67.71	54.67	42.95	41.66	37.04	35.39	33.60	-34.11	-50.4

[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 from 1896 to 2021 of 34.11 km^2 (13.17 mi^2) compared to 19.70 km^2 (7.61 mi^2) (1.73 times the loss of the north extent). This corresponds to an average annual loss of 0.27 km^2 per year (0.11 $mi^2 \times yr^{-1}$) over 125 years for the south and 0.16 km^2 per year (0.06 $mi^2 \times yr^{-}$

[1]) for the north aspect glaciers in 125 years. 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. Additionally, insulating debris cover, especially on the north-facing glaciers may have an influence in the lower ablation rates observed here.

5.5. Volumetric Change from 1970 to 2021

Volumetric change* was calculated by Sisson and others (2011) and Robinson and others (2010) to estimate total change in glacier volume from a period of early 1970 to 2007/8 (Figure 11). The authors determined that the differencing between the two time periods gives a net volumetric change for glaciers and perennial snowfields of -0.65 km^3 (-0.16 mi^3). They also note that because the 1970 DEM may be up to 0.7 m (2.3 ft) high relative to the LiDAR, the minimum net volumetric change is -0.59 km^3 (-0.14 mi^3). Finally, Sisson and others (2011) note that Mount Rainier's glaciers and perennial snowfields lost approximately 13.4 – 14.7% of their 1970-1981 composite volume.

Figure 12 and Table 11 show the results of the differencing between 2007/8 and 2021, using a scale that matches the pattern used in Figure 1 by Sisson and others (2011). Glaciers and perennial snowfields during this time lost, on average, between -0.54 to -15.71 m (-1.77 to -51.54 ft), with an average of -4.63 m (-15.19 ft). The total volumetric change between 2007/8 and 2021 is -0.404 km^3 (-0.097 mi^3) (Table 11). The average volumetric change for each glacier in the Park was -0.014 km^3 (-0.003 mi^3).

Combining the two periods gives a total net volumetric change at the Park between 1970 to 2021 of between -0.994 to -1.054 km^3 (-0.239 to -0.253 mi^3).

* For the purposes of this study, the term "volumetric change" refers to the total change in volume between time periods at MORA, whereas "volume" refers to the total volume present at a specific point in time. For example, glacier volumes at Time A and B of 0.9 and 0.8 km^3 respectively would result in a volumetric change of -0.1 km^3 during that period.

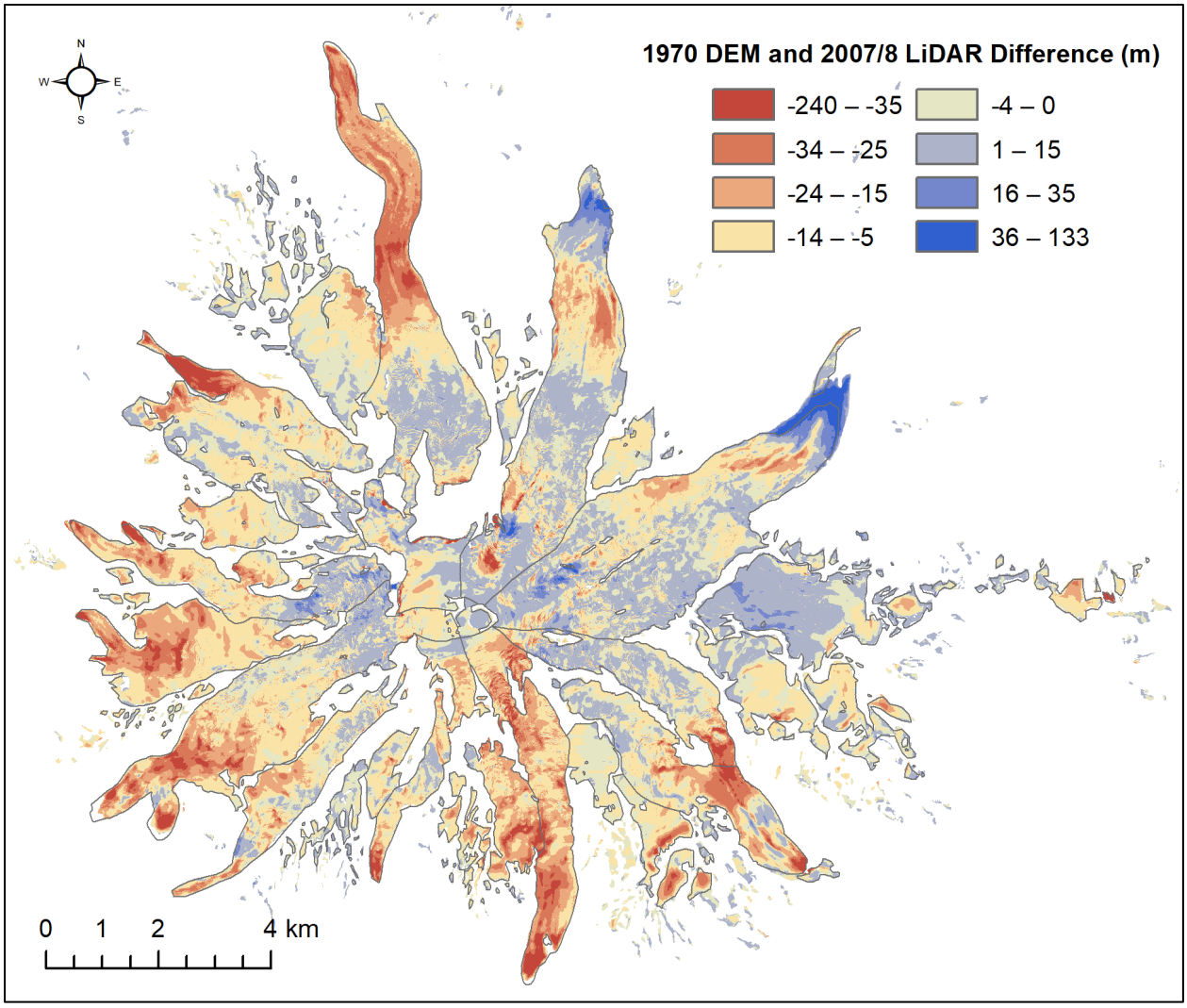


Figure 11. Map of net change in surface elevation of glaciers and snowfields from 1970 to 2007/8 at Mount Rainier using data from Sisson and others (2011).

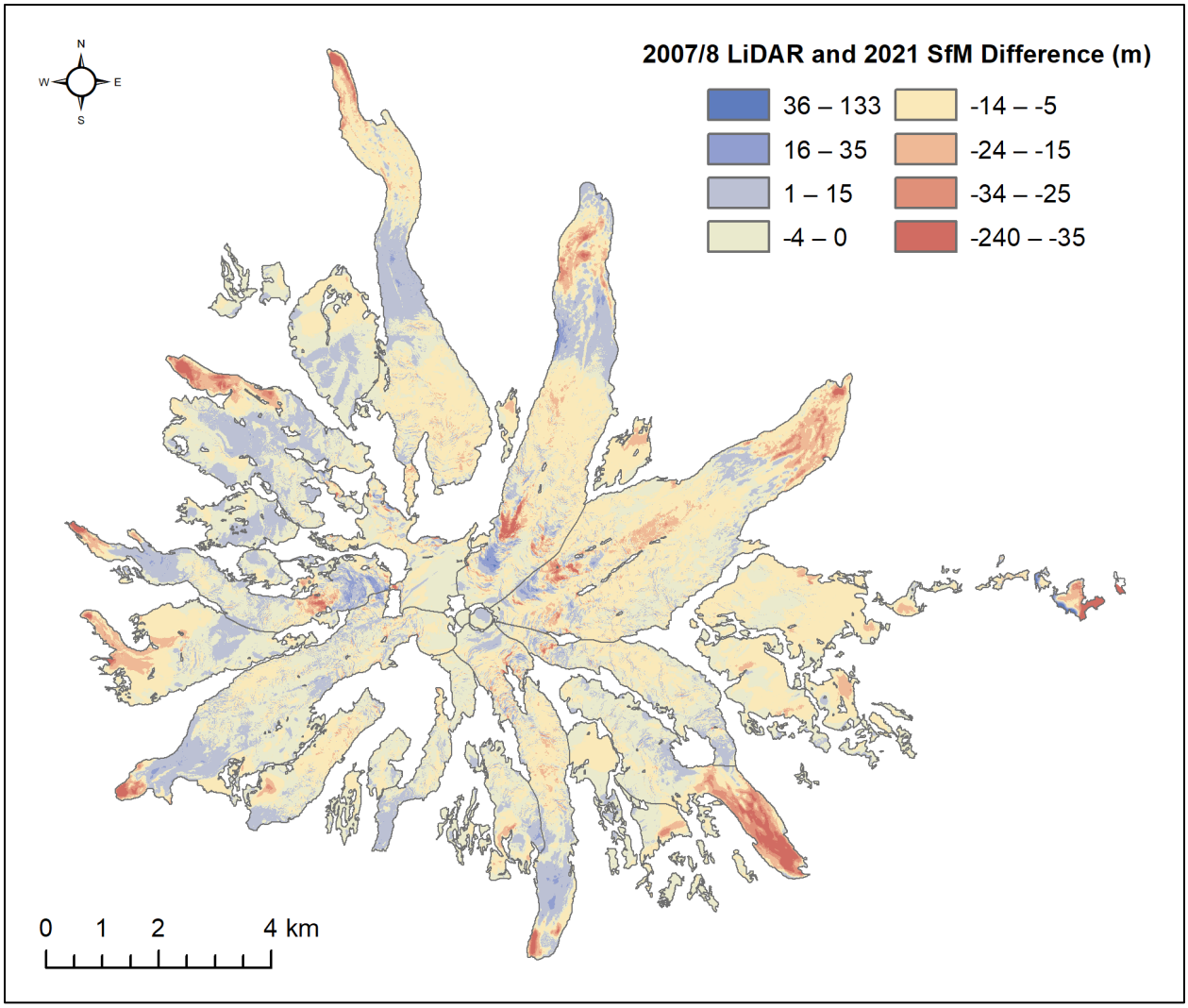


Figure 12. Map of net change in surface elevation (thickness) of glaciers and snowfields from 2007/8 to 2021 at Mount Rainier, calculated by subtracting the 2021 SfM DSM from the 2007/8 LiDAR bare earth DEM, clipped to the 2009 glacier extents (summarized in Table 11). The scale matches the pattern used by Sisson and others (2011) in Figure 11.

Table 11. Total volumetric change of glaciers at Mount Rainier National Park from 2007/8 to 2021.

Glacier Name	Average Elevation Change, m	Volume Change, m^3	Volume Change, km^3
Carbon	-5.18 ± 0.28	-38,231,496 ± 2,032,382	-0.038 ± 0.002
Columbia Crest	-1.75 ± 0.09	-314,820 ± 16,736	0.000 ± 0.000
Cowlitz	-10.41 ± 0.55	-42,230,801 ± 2,244,985	-0.042 ± 0.002
Edmunds	-0.54 ± 0.03	-697,793 ± 37,095	-0.001 ± 0.000
Emmons	-7.26 ± 0.39	-79,714,598 ± 4,237,619	-0.080 ± 0.004
Flett	-1.89 ± 0.10	-1,096,862 ± 58,309	-0.001 ± 0.000

Table 11 (continued). Total volumetric change of glaciers at Mount Rainier National Park from 2007/8 to 2021.

Glacier Name	Average Elevation Change, m	Volume Change, m^3	Volume Change, km^3
Fryingpan	-7.08 ± 0.38	-23,306,636 ± 1,238,978	-0.023 ± 0.001
Ingraham	-3.42 ± 0.18	-10,217,752 ± 543,175	-0.010 ± 0.001
Inter	-8.44 ± 0.45	-5,603,589 ± 297,886	-0.006 ± 0.000
Kautz	-1.94 ± 0.10	-3,024,763 ± 160,796	-0.003 ± 0.000
Liberty Cap	-4.01 ± 0.21	-8,819,643 ± 468,851	-0.009 ± 0.000
Muir	-4.70 ± 0.25	-4,309,852 ± 229,111	-0.004 ± 0.000
Nisqually	-3.99 ± 0.21	-17,326,485 ± 921,074	-0.017 ± 0.001
N. Mowich	-3.66 ± 0.19	-19,300,573 ± 1,026,016	-0.019 ± 0.001
Ohanapecosh	-6.50 ± 0.35	-5,089,988 ± 270,583	-0.005 ± 0.000
Paradise	-5.81 ± 0.31	-3,922,323 ± 208,510	-0.004 ± 0.000
Puyallup	-6.33 ± 0.34	-22,259,832 ± 1,183,330	-0.022 ± 0.001
Pyramid	-3.09 ± 0.16	-1,165,496 ± 61,958	-0.001 ± 0.000
Russell	-2.77 ± 0.15	-7,714,557 ± 410,105	-0.008 ± 0.000
Sarvent	-15.71 ± 0.83	-10,872,906 ± 578,002	-0.011 ± 0.001
S. Mowich	-1.80 ± 0.10	-7,119,130 ± 378,452	-0.007 ± 0.000
S. Tahoma	-5.18 ± 0.28	-10,457,498 ± 555,919	-0.010 ± 0.001
Stevens	-1.37 ± 0.07	-137,924 ± 7,332	0.000 ± 0.000
Success	-3.19 ± 0.17	-1,644,329 ± 87,412	-0.002 ± 0.000
Tahoma	-2.52 ± 0.13	-17,168,229 ± 912,661	-0.017 ± 0.001
Van Trump	-1.88 ± 0.10	-592,858 ± 31,516	-0.001 ± 0.000
Whitman	-5.63 ± 0.30	-12,125,449 ± 644,588	-0.012 ± 0.001
Wilson	-3.03 ± 0.16	-4,994,104 ± 265,486	-0.005 ± 0.000
Winthrop	-5.26 ± 0.28	-44,844,808 ± 2,383,945	-0.045 ± 0.002
Average:	**-4.63 ± 0.25**	**-13,941,555 ± 741,132**	**-0.014 ±0.001**
Total:		**-404,305,094 ± 21,492,814**	**-0.404 ± 0.021**

5.6. 2021 Glacier Volume

Using Equation 11 and extents from Table 4, the estimated glacier volumes in 2021 varied from 0.001 km^3 (Van Trump, 0.000 mi^3) to 0.659 km^3 (Emmons, 0.158 mi^3) and averaged 0.126 km^3 (0.030 mi^3) (Figure 13; Table 12). The total volume of glaciers at Mount Rainier in 2021 was 3.516 ± 1.231 km^3 (0.844 ± 0.296 mi^3) (Table 12).

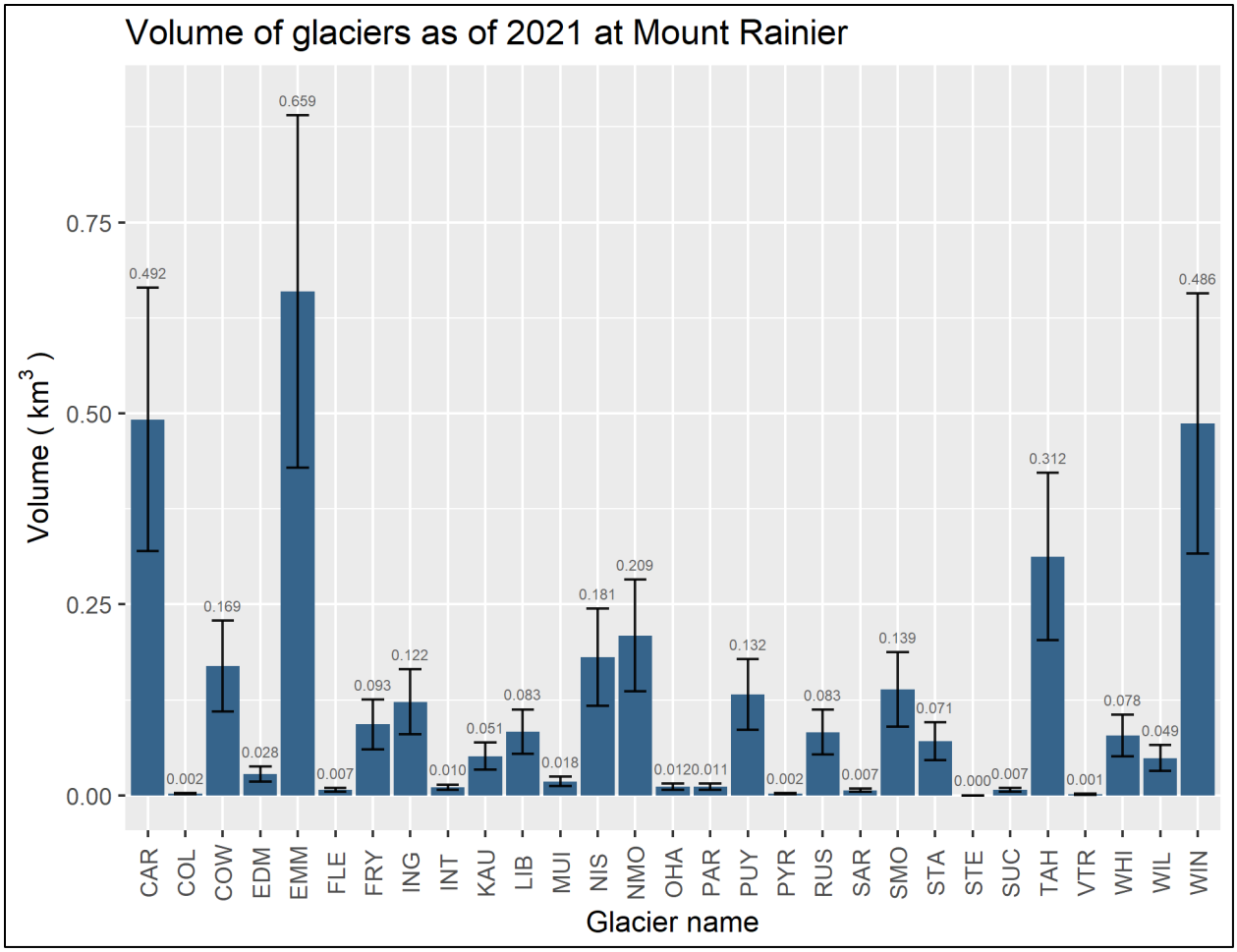


Figure 13. Estimated volume of glaciers at Mount Rainier in 2021, based on data in Table 12 and calculated with Equation 11 and glacial extents from Table 4. The value at the top of each column is the total volume of each glacier. Error bars represent an estimated 35% error in approximation of glacial volume from extent. Glacier name identification can be found in Table 12.

Table 12. Estimated volume of glacial ice in 2021 at Mount Rainier, using equation 11 and extents from Table 4.

Glacier name	Ident	Rank	2021 Estimated Glacial Volume		
			m^3	km^3	mi^3
Carbon	CAR	2	491,933,794 ± 172,176,828	0.492 ± 0.172	0.118 ± 0.041
Columbia Crest	COL	27	2,354,888 ± 824,211	0.002 ± 0.001	0.001 ± 0.000
Cowlitz	COW	7	169,289,501 ± 59,251,325	0.169 ± 0.059	0.041 ± 0.014
Edmunds	EDM	18	27,854,541 ± 9,749,089	0.028 ± 0.010	0.007 ± 0.002
Emmons	EMM	1	659,213,186 ± 230,724,615	0.659 ± 0.231	0.158 ± 0.055
Flett	FLE	23	6,938,372 ± 2,428,430	0.007 ± 0.002	0.002 ± 0.001
Fryingpan	FRY	11	92,990,091 ± 32,546,532	0.093 ± 0.033	0.022 ± 0.008
Ingraham	ING	10	122,385,999 ± 42,835,100	0.122 ± 0.043	0.029 ± 0.010

Table 12 (continued). Estimated volume of glacial ice in 2021 at Mount Rainier, using equation 11 and extents from Table 4.

Glacier name	Ident	Rank	2021 Estimated Glacial Volume		
			m^3	km^3	mi^3
Inter	INT	22	10,433,028 ± 3,651,560	0.010 ± 0.004	0.003 ± 0.001
Kautz	KAU	16	51,313,169 ± 17,959,609	0.051 ± 0.018	0.012 ± 0.004
Liberty Cap	LIB	12	83,307,324 ± 29,157,563	0.083 ± 0.029	0.020 ± 0.007
Muir	MUI	19	18,043,925 ± 6,315,374	0.018 ± 0.006	0.004 ± 0.002
Nisqually	NIS	6	180,799,587 ± 63,279,855	0.181 ± 0.063	0.043 ± 0.015
N. Mowich	NMO	5	209,113,097 ± 73,189,584	0.209 ± 0.073	0.050 ± 0.018
Ohanapecosh	OHA	20	11,511,976 ± 4,029,192	0.012 ± 0.004	0.003 ± 0.001
Paradise	PAR	21	11,357,604 ± 3,975,161	0.011 ± 0.004	0.003 ± 0.001
Puyallup	PUY	9	132,261,921 ± 46,291,672	0.132 ± 0.046	0.032 ± 0.011
Pyramid	PYR	26	2,417,235 ± 846,032	0.002 ± 0.001	0.001 ± 0.000
Russell	RUS	13	82,797,338 ± 28,979,068	0.083 ± 0.029	0.020 ± 0.007
Sarvent	SAR	25	6,626,725 ± 2,319,354	0.007 ± 0.002	0.002 ± 0.001
S. Mowich	SMO	8	138,675,898 ± 48,536,564	0.139 ± 0.049	0.033 ± 0.012
S. Tahoma	STA	15	70,606,832 ± 24,712,391	0.071 ± 0.025	0.017 ± 0.006
Stevens	STE	–	–	–	–
Success	SUC	24	6,936,194 ± 2,427,668	0.007 ± 0.002	0.002 ± 0.001
Tahoma	TAH	4	312,475,088 ± 109,366,281	0.312 ± 0.109	0.075 ± 0.026
Van Trump	VTR	28	1,397,617 ± 489,166	0.001 ± 0.000	0.000 ± 0.000
Whitman	WHI	14	77,941,924 ± 27,279,673	0.078 ± 0.027	0.019 ± 0.007
Wilson	WIL	17	48,725,420 ± 17,053,897	0.049 ± 0.017	0.012 ± 0.004
Winthrop	WIN	3	486,489,224 ± 170,271,228	0.486 ± 0.170	0.117 ± 0.041
Total:	**n/a**	**n/a**	**3,516,191,497 ± 1,230,667,024**	**3.516 ± 1.231**	**0.844 ± 0.295**

5.7. Glacial Volume Change – 1896 to 2021

Figure 14 and Tables 13-15 show the estimates of glacial volume change at Mount Rainier from 1896 to 2021 (error bars are included in the tables but not shown in Figure 14 for clarity). Figure 14 also shows the measured volumes of ice in 1971 from Driedger and Kennard (1986) and 1913, 1971, and 1994 from Nylen (2001).

Table 13 shows the calculated volumes based on the scaling parameter, *c*, back calculated from Driedger and Kennard's (2001) estimates of volume and area from 1971 and calculated with Equation 10 and extents from Table 7. Table 14 uses Equation 10 from Nylen (2001) and extents from Table 7. Table 15 is the mean of the two methods (Equation 11) calculated with extents from Table 7. As mentioned previously, Table 13 plots on the upper boundary and Table 14 plots on the lower boundary for glacial volume in particular years.

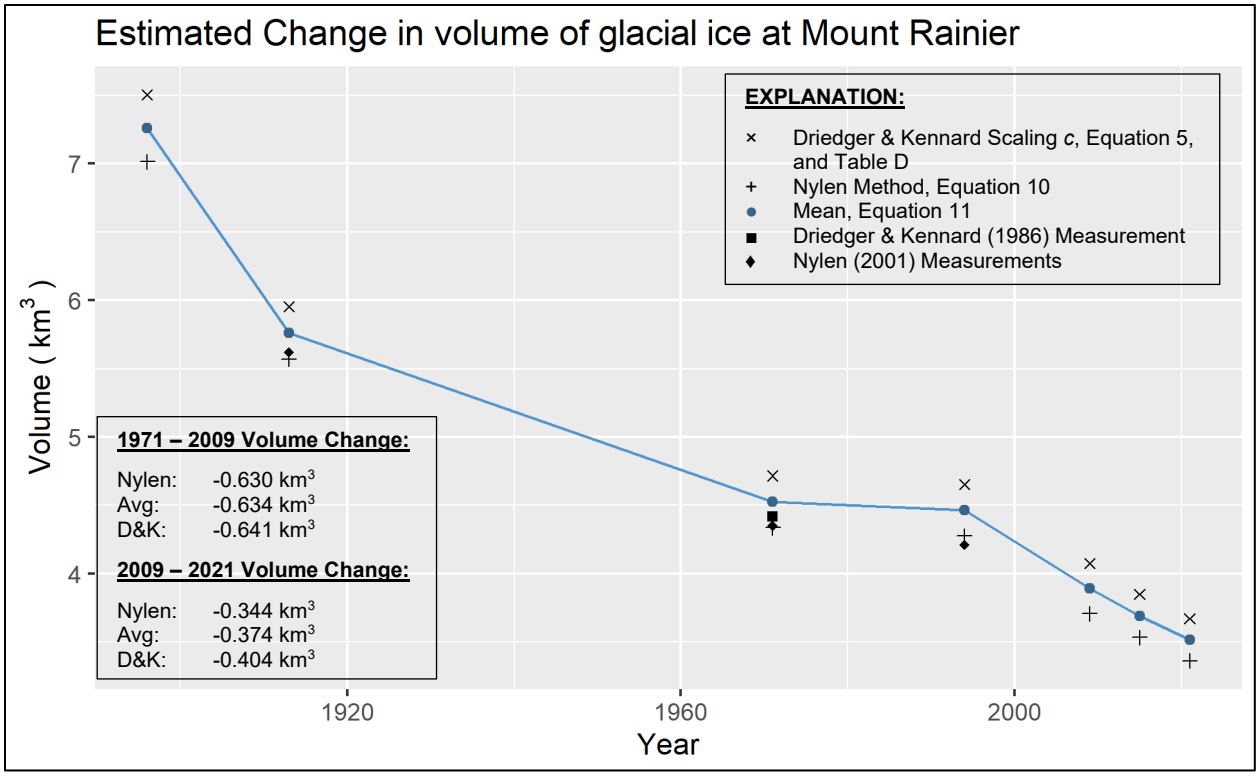


Figure 14. Estimated overall change in glacial volume at Mount Rainier from 1896-2021, based on various methods and data in Table 13 – Table 15. Error bars are not included for clarity. Measured volumes from Driedger and Kennard (1986; black square) and Nylen (2001; black diamonds) are included in this plot. Volumetric change between 1971-2009 and 2009-2021 shown in left inset box.

Table 13. Comparison of estimated volumes of individual glaciers at Mount Rainier over time (excluding unnamed perennial ice/snow fields) using the Driedger and Kennard Scaling Parameter, *c*, with *c* values from Table 3 and calculated with Equation 5 using extents from Table 7. Values listed are in cubic kilometers (km^3). The Flett, Ohanapecosh and Sarvent Glaciers were not mapped in 1896.

Glacier Name	1896	1913	1971	1994	2009	2015	2021
Carbon	0.757 ± 0.265	0.778 ± 0.272	0.723 ± 0.253	0.718 ± 0.251	0.654 ± 0.229	0.631 ± 0.221	0.615 ± 0.215
Columbia Crest	0.006 ± 0.002	0.001 ± 0.000	0.004 ± 0.001	0.003 ± 0.001	0.001 ± 0.000	0.003 ± 0.001	0.002 ± 0.001
Cowlitz-Ingraham	0.576 ± 0.202	0.727 ± 0.254	0.513 ± 0.180	0.519 ± 0.181	0.459 ± 0.161	0.346 ± 0.121	0.321 ± 0.112
Edmunds	0.082 ± 0.029	0.035 ± 0.012	0.034 ± 0.012	0.032 ± 0.011	0.028 ± 0.010	0.027 ± 0.009	0.024 ± 0.009
Emmons	1.246 ± 0.436	0.798 ± 0.279	0.673 ± 0.236	0.679 ± 0.237	0.658 ± 0.230	0.662 ± 0.232	0.657 ± 0.230
Flett	–	0.020 ± 0.007	0.014 ± 0.005	0.015 ± 0.005	0.014 ± 0.005	0.009 ± 0.003	0.007 ± 0.003
Fryingpan	0.098 ± 0.034	0.194 ± 0.068	0.121 ± 0.042	0.117 ± 0.041	0.083 ± 0.029	0.081 ± 0.028	0.073 ± 0.025
Inter	0.011 ± 0.004	0.029 ± 0.010	0.019 ± 0.007	0.018 ± 0.006	0.014 ± 0.005	0.011 ± 0.004	0.010 ± 0.004
Kautz-Success	0.290 ± 0.102	0.113 ± 0.039	0.095 ± 0.033	0.069 ± 0.024	0.085 ± 0.030	0.067 ± 0.023	0.063 ± 0.022
Liberty Cap	0.149 ± 0.052	0.119 ± 0.042	0.098 ± 0.034	0.099 ± 0.035	0.106 ± 0.037	0.102 ± 0.036	0.098 ± 0.034
Muir	0.026 ± 0.009	0.028 ± 0.010	0.021 ± 0.007	0.021 ± 0.007	0.019 ± 0.007	0.018 ± 0.006	0.017 ± 0.006
Nisqually-Wilson	0.641 ± 0.225	0.360 ± 0.126	0.322 ± 0.113	0.335 ± 0.117	0.317 ± 0.111	0.254 ± 0.089	0.243 ± 0.085
North Mowich	0.601 ± 0.210	0.387 ± 0.135	0.275 ± 0.096	0.265 ± 0.093	0.213 ± 0.075	0.210 ± 0.073	0.196 ± 0.069
Ohanapecosh	–	0.086 ± 0.030	0.030 ± 0.010	0.030 ± 0.011	0.014 ± 0.005	0.011 ± 0.004	0.010 ± 0.003
Paradise-Stevens	0.196 ± 0.069	0.110 ± 0.038	0.034 ± 0.012	0.033 ± 0.012	0.014 ± 0.005	0.012 ± 0.004	0.011 ± 0.004
Puyallup	0.581 ± 0.203	0.298 ± 0.104	0.230 ± 0.081	0.233 ± 0.081	0.174 ± 0.061	0.156 ± 0.055	0.146 ± 0.051
Pyramid	0.106 ± 0.037	0.042 ± 0.015	0.017 ± 0.006	0.015 ± 0.005	0.007 ± 0.002	0.004 ± 0.001	0.002 ± 0.001
Russell	0.228 ± 0.080	0.152 ± 0.053	0.098 ± 0.034	0.100 ± 0.035	0.070 ± 0.024	0.073 ± 0.026	0.067 ± 0.023
Sarvent	–	0.029 ± 0.010	0.014 ± 0.005	0.002 ± 0.001	0.015 ± 0.005	0.008 ± 0.003	0.006 ± 0.002
South Mowich	0.221 ± 0.077	0.186 ± 0.065	0.154 ± 0.054	0.152 ± 0.053	0.147 ± 0.052	0.137 ± 0.048	0.130 ± 0.046
South Tahoma	0.361 ± 0.126	0.170 ± 0.059	0.136 ± 0.048	0.094 ± 0.033	0.093 ± 0.032	0.081 ± 0.028	0.078 ± 0.027
Tahoma	0.718 ± 0.251	0.496 ± 0.173	0.384 ± 0.134	0.361 ± 0.126	0.327 ± 0.114	0.328 ± 0.115	0.304 ± 0.107
Van Trump	0.045 ± 0.016	0.043 ± 0.015	0.016 ± 0.006	0.017 ± 0.006	0.006 ± 0.002	0.002 ± 0.001	0.001 ± 0.000

Table 13 (continued). Comparison of estimated volumes of individual glaciers at Mount Rainier over time (excluding unnamed perennial ice/snow fields) using the Driedger and Kennard Scaling Parameter, *c*, with *c* values from Table 3 and calculated with Equation 5 using extents from Table 7. Values listed are in cubic kilometers (km^3). The Flett, Ohanapecosh and Sarvent Glaciers were not mapped in 1896.

Glacier Name	1896	1913	1971	1994	2009	2015	2021
Whitman	0.107 ± 0.037	0.142 ± 0.050	0.126 ± 0.044	0.133 ± 0.046	0.116 ± 0.041	0.104 ± 0.036	0.097 ± 0.034
Winthrop	0.456 ± 0.159	0.610 ± 0.214	0.565 ± 0.198	0.591 ± 0.207	0.439 ± 0.154	0.513 ± 0.180	0.491 ± 0.172
Total:	**7.503 ± 2.626**	**5.953 ± 2.083**	**4.715 ± 1.650**	**4.651 ± 1.628**	**4.074 ± 1.426**	**3.849 ± 1.347**	**3.670 ± 1.285**

Table 14. Comparison of estimated volumes of individual glaciers at Mount Rainier over time (excluding unnamed perennial ice/snow fields) using the Nylen (2001) method and Equation 10 using extents from Table 7. Values listed are in cubic kilometers (km^3). The Flett, Ohanapecosh and Sarvent Glaciers were not mapped in 1896.

Glacier Name	1896	1913	1971	1994	2009	2015	2021
Carbon	0.453 ± 0.158	0.465 ± 0.163	0.432 ± 0.151	0.430 ± 0.150	0.392 ± 0.137	0.378 ± 0.132	0.369 ± 0.129
Columbia Crest	0.005 ± 0.002	0.001 ± 0.000	0.004 ± 0.001	0.003 ± 0.001	0.001 ± 0.000	0.002 ± 0.001	0.002 ± 0.001
Cowlitz-Ingraham	0.454 ± 0.159	0.571 ± 0.200	0.405 ± 0.142	0.409 ± 0.143	0.363 ± 0.127	0.281 ± 0.099	0.262 ± 0.092
Edmunds	0.104 ± 0.037	0.045 ± 0.016	0.043 ± 0.015	0.041 ± 0.014	0.036 ± 0.013	0.035 ± 0.012	0.031 ± 0.011
Emmons	1.246 ± 0.436	0.802 ± 0.281	0.678 ± 0.237	0.683 ± 0.239	0.663 ± 0.232	0.667 ± 0.234	0.662 ± 0.232
Flett	–	0.017 ± 0.006	0.012 ± 0.004	0.013 ± 0.005	0.012 ± 0.004	0.007 ± 0.003	0.006 ± 0.002
Fryingpan	0.152 ± 0.053	0.300 ± 0.105	0.188 ± 0.066	0.181 ± 0.063	0.129 ± 0.045	0.126 ± 0.044	0.113 ± 0.040
Inter	0.012 ± 0.004	0.031 ± 0.011	0.020 ± 0.007	0.020 ± 0.007	0.015 ± 0.005	0.012 ± 0.004	0.011 ± 0.004
Kautz-Success	0.238 ± 0.083	0.097 ± 0.034	0.083 ± 0.029	0.061 ± 0.021	0.071 ± 0.025	0.058 ± 0.020	0.054 ± 0.019
Liberty Cap	0.105 ± 0.037	0.084 ± 0.029	0.069 ± 0.024	0.070 ± 0.025	0.075 ± 0.026	0.072 ± 0.025	0.069 ± 0.024
Muir	0.030 ± 0.011	0.033 ± 0.012	0.024 ± 0.009	0.025 ± 0.009	0.023 ± 0.008	0.021 ± 0.007	0.020 ± 0.007
Nisqually-Wilson	0.586 ± 0.205	0.331 ± 0.116	0.296 ± 0.104	0.309 ± 0.108	0.292 ± 0.102	0.226 ± 0.079	0.217 ± 0.076
North Mowich	0.671 ± 0.235	0.434 ± 0.152	0.309 ± 0.108	0.299 ± 0.105	0.240 ± 0.084	0.237 ± 0.083	0.222 ± 0.078
Ohanapecosh	–	0.112 ± 0.039	0.039 ± 0.014	0.040 ± 0.014	0.018 ± 0.006	0.015 ± 0.005	0.013 ± 0.005
Paradise-Stevens	0.219 ± 0.077	0.123 ± 0.043	0.039 ± 0.014	0.038 ± 0.013	0.016 ± 0.006	0.013 ± 0.005	0.012 ± 0.004

Table 14 (continued). Comparison of estimated volumes of individual glaciers at Mount Rainier over time (excluding unnamed perennial ice/snow fields) using the Nylen (2001) method and Equation 10 using extents from Table 7. Values listed are in cubic kilometers (km^3). The Flett, Ohanapecosh and Sarvent Glaciers were not mapped in 1896.

Glacier Name	1896	1913	1971	1994	2009	2015	2021
Puyallup	0.466 ± 0.163	0.241 ± 0.084	0.186 ± 0.065	0.188 ± 0.066	0.141 ± 0.049	0.127 ± 0.044	0.119 ± 0.042
Pyramid	0.101 ± 0.035	0.040 ± 0.014	0.016 ± 0.006	0.014 ± 0.005	0.007 ± 0.002	0.004 ± 0.001	0.002 ± 0.001
Russell	0.332 ± 0.116	0.222 ± 0.078	0.144 ± 0.050	0.148 ± 0.052	0.103 ± 0.036	0.108 ± 0.038	0.099 ± 0.035
Sarvent	–	0.031 ± 0.011	0.015 ± 0.005	0.002 ± 0.001	0.016 ± 0.005	0.009 ± 0.003	0.007 ± 0.002
South Mowich	0.248 ± 0.087	0.209 ± 0.073	0.173 ± 0.061	0.171 ± 0.060	0.166 ± 0.058	0.155 ± 0.054	0.147 ± 0.051
South Tahoma	0.287 ± 0.100	0.136 ± 0.048	0.110 ± 0.038	0.076 ± 0.027	0.075 ± 0.026	0.066 ± 0.023	0.063 ± 0.022
Tahoma	0.749 ± 0.262	0.519 ± 0.182	0.404 ± 0.141	0.379 ± 0.133	0.344 ± 0.120	0.345 ± 0.121	0.321 ± 0.112
Van Trump	0.042 ± 0.015	0.040 ± 0.014	0.015 ± 0.005	0.016 ± 0.006	0.005 ± 0.002	0.002 ± 0.001	0.001 ± 0.000
Whitman	0.064 ± 0.023	0.085 ± 0.030	0.076 ± 0.026	0.080 ± 0.028	0.070 ± 0.025	0.063 ± 0.022	0.059 ± 0.021
Winthrop	0.449 ± 0.157	0.599 ± 0.210	0.555 ± 0.194	0.580 ± 0.203	0.432 ± 0.151	0.504 ± 0.177	0.482 ± 0.169
Total:	**7.014 ± 2.455**	**5.569 ± 1.949**	**4.336 ± 1.517**	**4.275 ± 1.496**	**3.706 ± 1.297**	**3.533 ± 1.237**	**3.362 ± 1.177**

Table 15. Comparison of estimated volumes of individual glaciers at Mount Rainier over time (excluding unnamed perennial ice/snow fields) using the mean between Tables 13 and 14 (Equation 11) using extents from Table 7. Values listed are in cubic kilometers (km^3). The Flett, Ohanapecosh and Sarvent Glaciers were not mapped in 1896.

Glacier Name	1896	1913	1971	1994	2009	2015	2021
Carbon	0.605 ± 0.212	0.622 ± 0.218	0.578 ± 0.202	0.574 ± 0.201	0.523 ± 0.183	0.504 ± 0.176	0.492 ± 0.172
Columbia Crest	0.006 ± 0.002	0.001 ± 0.000	0.004 ± 0.001	0.003 ± 0.001	0.001 ± 0.000	0.003 ± 0.001	0.002 ± 0.001
Cowlitz-Ingraham	0.515 ± 0.180	0.649 ± 0.227	0.459 ± 0.161	0.464 ± 0.162	0.411 ± 0.144	0.314 ± 0.110	0.292 ± 0.102
Edmunds	0.093 ± 0.033	0.040 ± 0.014	0.038 ± 0.013	0.036 ± 0.013	0.032 ± 0.011	0.031 ± 0.011	0.028 ± 0.010
Emmons	1.246 ± 0.436	0.800 ± 0.280	0.676 ± 0.236	0.681 ± 0.238	0.661 ± 0.231	0.665 ± 0.233	0.659 ± 0.231
Flett	–	0.018 ± 0.006	0.013 ± 0.005	0.014 ± 0.005	0.013 ± 0.005	0.008 ± 0.003	0.007 ± 0.002
Fryingpan	0.125 ± 0.044	0.247 ± 0.086	0.154 ± 0.054	0.149 ± 0.052	0.106 ± 0.037	0.104 ± 0.036	0.093 ± 0.033

Table 15 (continued). Comparison of estimated volumes of individual glaciers at Mount Rainier over time (excluding unnamed perennial ice/snow fields) using the mean between Tables 13 and 14 (Equation 11) using extents from Table 7. Values listed are in cubic kilometers (km^3). The Flett, Ohanapecosh and Sarvent Glaciers were not mapped in 1896.

Glacier Name	1896	1913	1971	1994	2009	2015	2021
Inter	0.011 ± 0.004	0.030 ± 0.010	0.019 ± 0.007	0.019 ± 0.007	0.014 ± 0.005	0.012 ± 0.004	0.010 ± 0.004
Kautz-Success	0.264 ± 0.093	0.105 ± 0.037	0.089 ± 0.031	0.065 ± 0.023	0.078 ± 0.027	0.062 ± 0.022	0.058 ± 0.020
Liberty Cap	0.127 ± 0.044	0.102 ± 0.036	0.084 ± 0.029	0.085 ± 0.030	0.090 ± 0.032	0.087 ± 0.030	0.083 ± 0.029
Muir	0.028 ± 0.010	0.031 ± 0.011	0.023 ± 0.008	0.023 ± 0.008	0.021 ± 0.007	0.020 ± 0.007	0.018 ± 0.006
Nisqually-Wilson	0.614 ± 0.215	0.346 ± 0.121	0.309 ± 0.108	0.322 ± 0.113	0.304 ± 0.107	0.240 ± 0.084	0.230 ± 0.080
North Mowich	0.636 ± 0.223	0.410 ± 0.144	0.292 ± 0.102	0.282 ± 0.099	0.227 ± 0.079	0.223 ± 0.078	0.209 ± 0.073
Ohanapecosh	–	0.099 ± 0.035	0.034 ± 0.012	0.035 ± 0.012	0.016 ± 0.006	0.013 ± 0.005	0.012 ± 0.004
Paradise-Stevens	0.208 ± 0.073	0.116 ± 0.041	0.036 ± 0.013	0.036 ± 0.012	0.015 ± 0.005	0.012 ± 0.004	0.011 ± 0.004
Puyallup	0.523 ± 0.183	0.270 ± 0.094	0.208 ± 0.073	0.210 ± 0.074	0.157 ± 0.055	0.142 ± 0.050	0.132 ± 0.046
Pyramid	0.104 ± 0.036	0.041 ± 0.014	0.016 ± 0.006	0.014 ± 0.005	0.007 ± 0.002	0.004 ± 0.001	0.002 ± 0.001
Russell	0.280 ± 0.098	0.187 ± 0.065	0.121 ± 0.042	0.124 ± 0.043	0.086 ± 0.030	0.091 ± 0.032	0.083 ± 0.029
Sarvent	–	0.030 ± 0.010	0.015 ± 0.005	0.002 ± 0.001	0.015 ± 0.005	0.008 ± 0.003	0.007 ± 0.002
South Mowich	0.235 ± 0.082	0.198 ± 0.069	0.164 ± 0.057	0.162 ± 0.057	0.157 ± 0.055	0.146 ± 0.051	0.139 ± 0.049
South Tahoma	0.324 ± 0.113	0.153 ± 0.054	0.123 ± 0.043	0.085 ± 0.030	0.084 ± 0.029	0.073 ± 0.026	0.071 ± 0.025
Tahoma	0.733 ± 0.257	0.507 ± 0.178	0.394 ± 0.138	0.370 ± 0.130	0.336 ± 0.117	0.336 ± 0.118	0.312 ± 0.109
Van Trump	0.043 ± 0.015	0.042 ± 0.015	0.016 ± 0.005	0.017 ± 0.006	0.005 ± 0.002	0.002 ± 0.001	0.001 ± 0.000
Whitman	0.085 ± 0.030	0.114 ± 0.040	0.101 ± 0.035	0.106 ± 0.037	0.093 ± 0.033	0.083 ± 0.029	0.078 ± 0.027
Winthrop	0.452 ± 0.158	0.604 ± 0.212	0.560 ± 0.196	0.585 ± 0.205	0.436 ± 0.152	0.509 ± 0.178	0.486 ± 0.170
Total:	**7.259 ± 2.541**	**5.761 ± 2.016**	**4.526 ± 1.584**	**4.463 ± 1.562**	**3.890 ± 1.362**	**3.691 ± 1.292**	**3.516 ± 1.231**

As the mean, Table 15's data will be used when discussing volumes for individual glaciers or parkwide glacial totals for the 1896-2021 period from here forward. Data from Table 13 or 14 could also be used in a similar way (bookending the estimates), but such figures have not been created for this study.

The lower left inset in Figure 14 are the calculations of volumetric change between 1971-2009 and 2009-2021, which can be directly compared to volumetric change results in Section 5.5. The average volumetric change between 1971-2009 is -0.634 km^3 (-0.152 mi^3), while the 2009-2021 volumetric change is -0.374 km^3 (-0.090 mi3), for a total of -1.008 km^3 (-0.241 mi^3). The results for each of these periods mirrors the observations of volumetric change between 1971-2009 and 2009-2021, giving some confidence in the approaches used to calculate volume at different time periods presented here.

Overall, in the last 125 years, Mount Rainier has lost approximately 3.743 km^3 (0.898 mi^3), a rate of about -0.030 km^3 per year (-0.007 $mi^3 \times yr^{-1}$) (Figure 14, Table 15). The trends observed in Figure 14 (volume) mirror those in Figure 4 (extent).

Figure 15 shows the changes in glacial volume for those glaciers and glacial systems (e.g., Nisqually and Wilson Glaciers together) whose 2021 surface area is greater than (or near) 5 km^2 (1.9 mi^2). It should be noted that the North Mowich Glacier has an extent less than 5 km^2; it is included in Figure 15 to be consistent with a similar figure in Beason (2017). Figure 16 shows the volume of glaciers and glacial systems whose area is between 1 – 5 km^2 (0.4 – 1.9 mi^2) and Figure 17 shows the volume of glaciers and glacial systems whose area is less than 1 km^2 (0.4 mi^2).

Table 16 shows the change in estimated volume between inventory periods for each glacier at Mount Rainier, based on mean volume change from Table 15. Table 17 shows the total percentage change in estimated volume between inventory periods for each glacier at Mount Rainier, based on data mean volume change from Table 15. These tables are useful as they show individual glaciers that are handling changing climate better or worse than others in the Park (for example, south facing cirque glaciers versus north facing summit glaciers).

The calculations in Table 15 result in volume changes over time that roughly agree with the volumetric changes in glacier mass between 1971 to 2007/8 (Sisson et al., 2011) and 2007/8 to 2021 (this study). Table 15's average volumetric change between 1971-2009 is -0.610 km^3 (-0.146 mi^3), which is in close agreement to the -0.59 to -0.65 km^3 (-0.14 to -0.16 mi^3) mass loss calculated by Sisson and others (2011). The 2009 to 2021 period has an average volumetric change in Table 15 of -0.374 km^3 (-0.090 mi^3), which compares with the volumetric change of -0.404 km^3 (-0.097 mi^3). This second period has a lower confidence but is within the error margin of the volume calculation method.

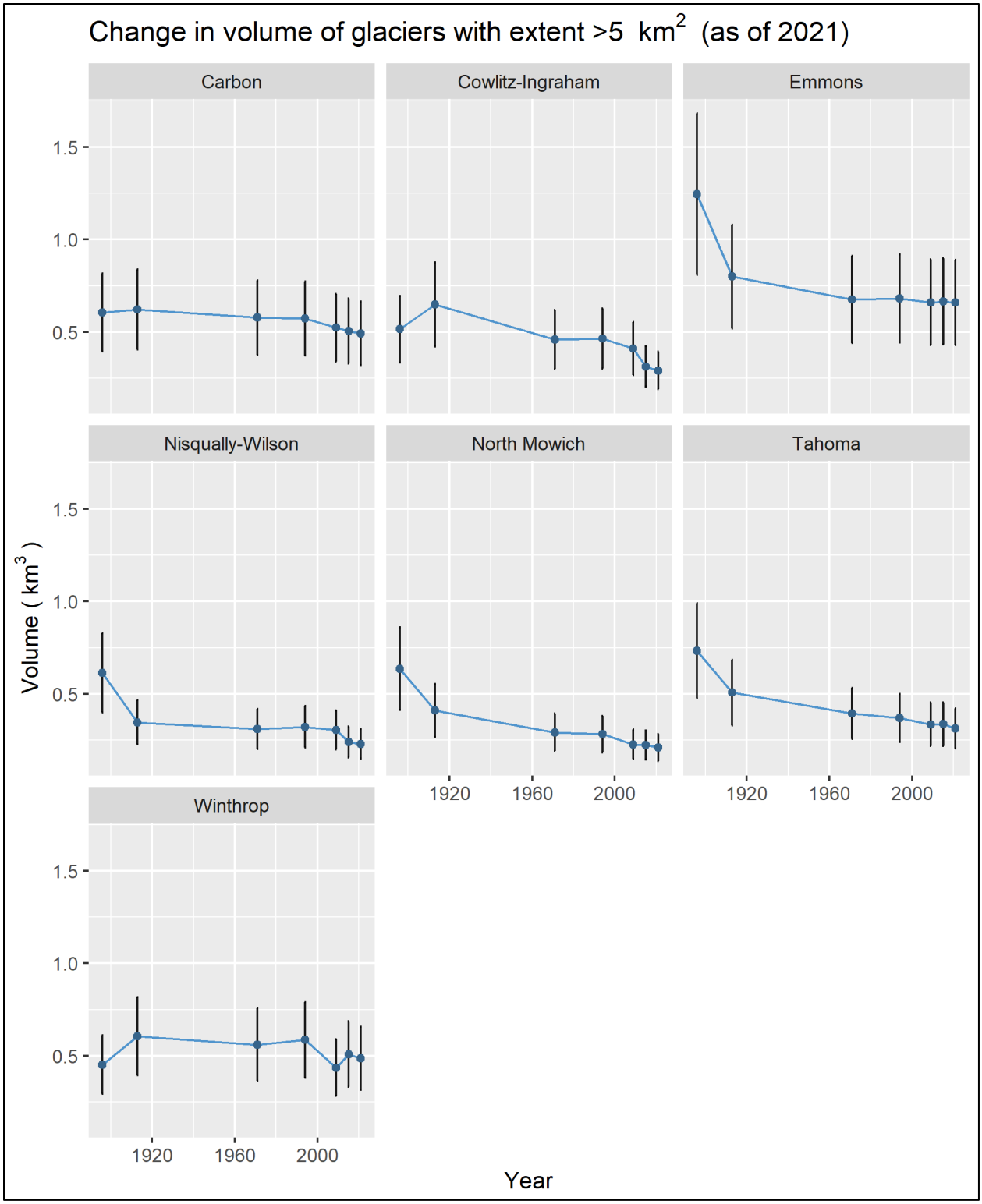


Figure 15. Change in volume of glaciers from 1896 to 2021 that had a 2021 extent greater than or near five square kilometers, based on data in Table 15.

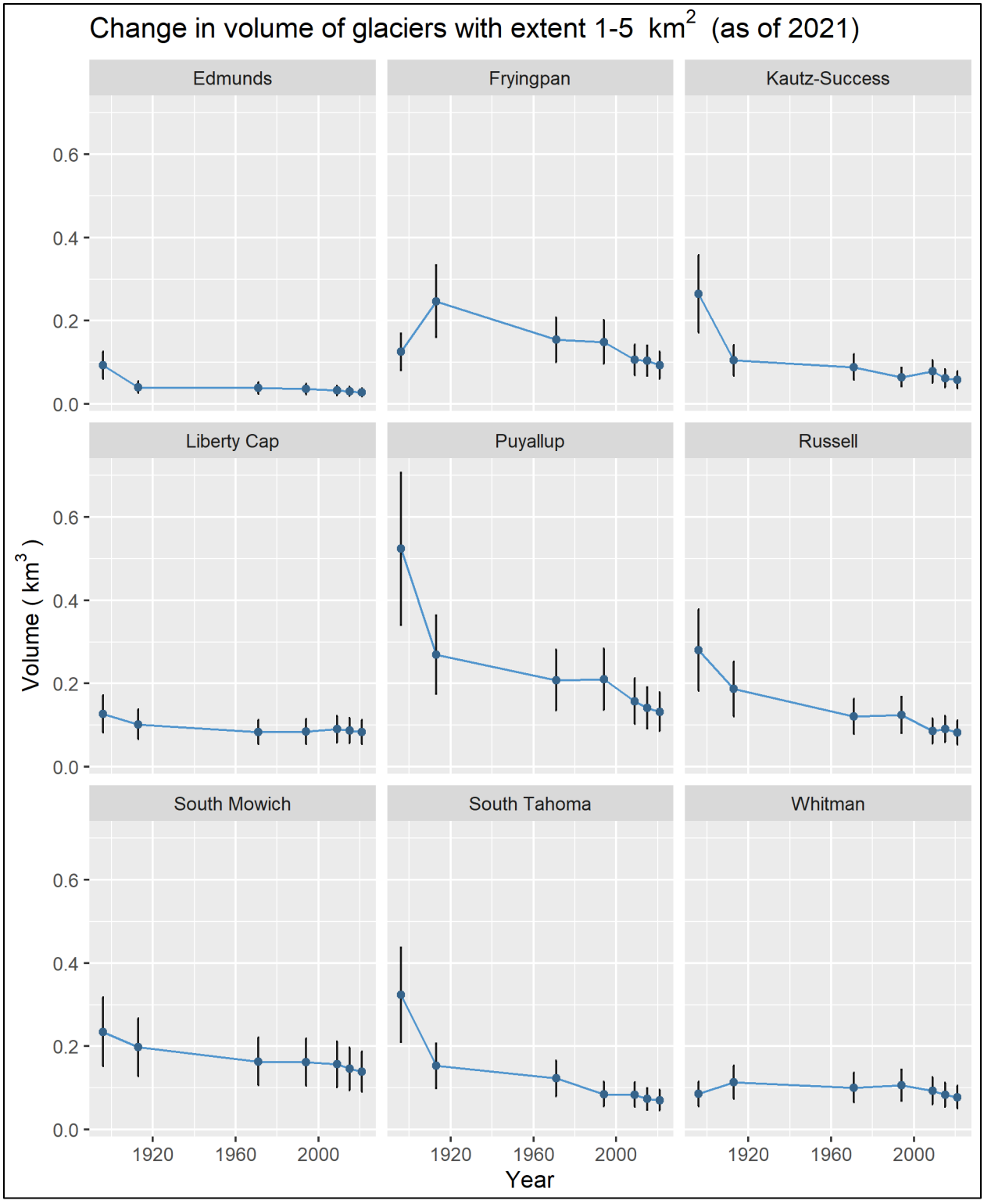


Figure 16. Change in volume of glaciers from 1896 to 2021 that had a 2021 extent between 1 and 5 square kilometers, based on data in Table 15.

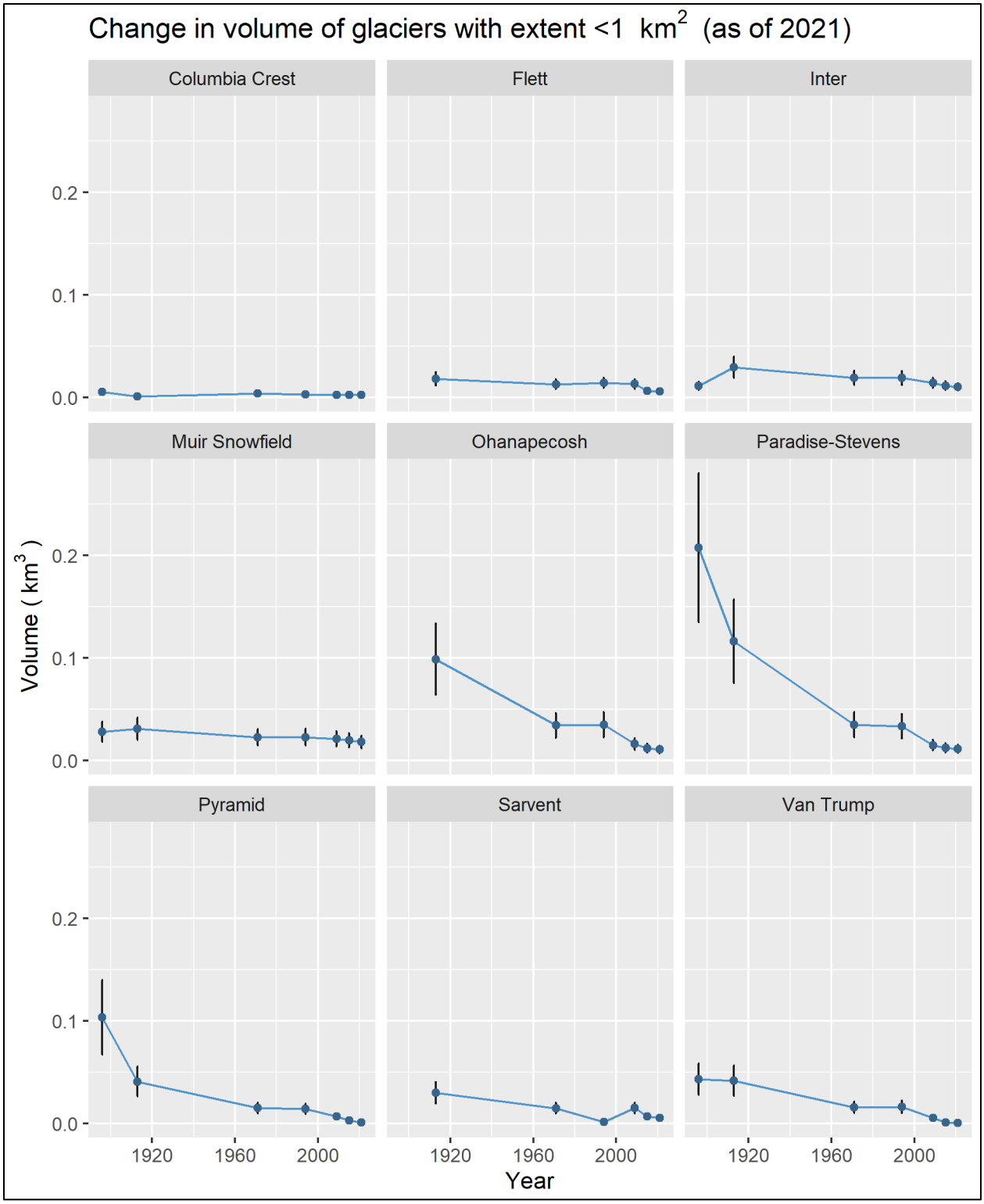


Figure 17. Change in volume of glaciers from 1896 to 2021 that had a 2021 extent less than 1 square kilometer, based on data in Table 15.

Table 16. Total change in estimated volume between inventory periods for each glacier at Mount Rainier, based on data mean volume change from Table 15. Listed units are in cubic kilometers (km^3). Average change is the total change in each period divided by the years between by those periods; units are in average cubic kilometers per year ($km^3 \times yr^{-1}$) (km^3 unit sign omitted for clarity).

Glacier Name	1896–1913	1896–1971	1896–1994	1896–2009	1896–2015	1896–2021	1913–1971	1913–1994	1913–2009	1913–2015	1913–2021	1971–1994	1971–2009	1971–2015	1971–2021	1994–2009	1994–2015	1994–2021	2009–2015	2009–2021	2015–2021
Carbon	0.02	-0.03	-0.03	-0.08	-0.10	-0.11	-0.04	-0.05	-0.10	-0.12	-0.13	0.00	-0.05	-0.07	-0.09	-0.05	-0.07	-0.08	-0.02	-0.03	-0.01
Columbia Crest	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cowlitz-Ingraham	0.13	-0.06	-0.05	-0.10	-0.20	-0.22	-0.19	-0.19	-0.24	-0.34	-0.36	0.00	-0.05	-0.15	-0.17	-0.05	-0.15	-0.17	-0.10	-0.12	-0.02
Edmunds	-0.05	-0.05	-0.06	-0.06	-0.06	-0.07	0.00	0.00	-0.01	-0.01	-0.01	0.00	-0.01	-0.01	-0.01	0.00	-0.01	-0.01	0.00	0.00	0.00
Emmons	-0.45	-0.57	-0.57	-0.59	-0.58	-0.59	-0.12	-0.12	-0.14	-0.13	-0.14	0.01	-0.01	-0.01	-0.02	-0.02	-0.02	-0.02	0.00	0.00	-0.01
Flett	–	–	–	–	–	–	-0.01	0.00	-0.01	-0.01	-0.01	0.00	0.00	0.00	-0.01	0.00	-0.01	-0.01	-0.01	-0.01	0.00
Fryingpan	0.12	0.03	0.02	-0.02	-0.02	-0.03	-0.09	-0.10	-0.14	-0.14	-0.15	-0.01	-0.05	-0.05	-0.06	-0.04	-0.05	-0.06	0.00	-0.01	-0.01
Inter	0.02	0.01	0.01	0.00	0.00	0.00	-0.01	-0.01	-0.02	-0.02	-0.02	0.00	-0.01	-0.01	-0.01	0.00	-0.01	-0.01	0.00	0.00	0.00
Kautz-Success	-0.16	-0.18	-0.20	-0.19	-0.20	-0.21	-0.02	-0.04	-0.03	-0.04	-0.05	-0.02	-0.01	-0.03	-0.03	0.01	0.00	-0.01	-0.02	-0.02	0.00
Liberty Cap	-0.03	-0.04	-0.04	-0.04	-0.04	-0.04	-0.02	-0.02	-0.01	-0.01	-0.02	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	-0.01	0.00
Muir	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nisqually-Wilson	-0.27	-0.30	-0.29	-0.31	-0.37	-0.38	-0.04	-0.02	-0.04	-0.11	-0.12	0.01	0.00	-0.07	-0.08	-0.02	-0.08	-0.09	-0.06	-0.07	-0.01
North Mowich	-0.23	-0.34	-0.35	-0.41	-0.41	-0.43	-0.12	-0.13	-0.18	-0.19	-0.20	-0.01	-0.07	-0.07	-0.08	-0.06	-0.06	-0.07	0.00	-0.02	-0.01
Ohanapecosh	–	–	–	–	–	–	-0.06	-0.06	-0.08	-0.09	-0.09	0.00	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	0.00	0.00	0.00
Paradise-Stevens	-0.09	-0.17	-0.17	-0.19	-0.20	-0.20	-0.08	-0.08	-0.10	-0.10	-0.11	0.00	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	0.00	0.00	0.00
Puyallup	-0.25	-0.32	-0.31	-0.37	-0.38	-0.39	-0.06	-0.06	-0.11	-0.13	-0.14	0.00	-0.05	-0.07	-0.08	-0.05	-0.07	-0.08	-0.02	-0.03	-0.01
Pyramid	-0.06	-0.09	-0.09	-0.10	-0.10	-0.10	-0.02	-0.03	-0.03	-0.04	-0.04	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.00
Russell	-0.09	-0.16	-0.16	-0.19	-0.19	-0.20	-0.07	-0.06	-0.10	-0.10	-0.10	0.00	-0.03	-0.03	-0.04	-0.04	-0.03	-0.04	0.00	0.00	-0.01
Sarvent	–	–	–	–	–	–	-0.02	-0.03	-0.01	-0.02	-0.02	-0.01	0.00	-0.01	-0.01	0.01	0.01	0.00	-0.01	-0.01	0.00
South Mowich	-0.04	-0.07	-0.07	-0.08	-0.09	-0.10	-0.03	-0.04	-0.04	-0.05	-0.06	0.00	-0.01	-0.02	-0.02	-0.01	-0.02	-0.02	-0.01	-0.02	-0.01
South Tahoma	-0.17	-0.20	-0.24	-0.24	-0.25	-0.25	-0.03	-0.07	-0.07	-0.08	-0.08	-0.04	-0.04	-0.05	-0.05	0.00	-0.01	-0.01	-0.01	-0.01	0.00
Tahoma	-0.23	-0.34	-0.36	-0.40	-0.40	-0.42	-0.11	-0.14	-0.17	-0.17	-0.19	-0.02	-0.06	-0.06	-0.08	-0.03	-0.03	-0.06	0.00	-0.02	-0.02
Van Trump	0.00	-0.03	-0.03	-0.04	-0.04	-0.04	-0.03	-0.02	-0.04	-0.04	-0.04	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	0.00	0.00	0.00
Whitman	0.03	0.02	0.02	0.01	0.00	-0.01	-0.01	-0.01	-0.02	-0.03	-0.04	0.01	-0.01	-0.02	-0.02	-0.01	-0.02	-0.03	-0.01	-0.02	-0.01
Winthrop	0.15	0.11	0.13	-0.02	0.06	0.03	-0.04	-0.02	-0.17	-0.10	-0.12	0.02	-0.12	-0.05	-0.07	-0.15	-0.08	-0.10	0.07	0.05	-0.02
Total Change:	**-1.64**	**-2.80**	**-2.85**	**-3.41**	**-3.60**	**-3.77**	**-1.24**	**-1.30**	**-1.87**	**-2.07**	**-2.24**	**-0.06**	**-0.64**	**-0.83**	**-1.01**	**-0.57**	**-0.77**	**-0.95**	**-0.20**	**-0.37**	**-0.18**
Years:	**17**	**75**	**98**	**113**	**119**	**125**	**58**	**81**	**96**	**102**	**108**	**23**	**38**	**44**	**50**	**15**	**21**	**27**	**6**	**12**	**6**
Avg. Change:	**-0.10**	**-0.04**	**-0.03**	**-0.03**	**-0.03**	**-0.03**	**-0.02**	**-0.02**	**-0.02**	**-0.02**	**-0.02**	**0.00**	**-0.02**	**-0.02**	**-0.02**	**-0.04**	**-0.04**	**-0.04**	**-0.03**	**-0.03**	**-0.03**

Table 17. Total percent change in estimated volume between inventory periods for each glacier at Mount Rainier, based on data mean volume change from Table 15. 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	1896–2021	1913–1971	1913–1994	1913–2009	1913–2015	1913–2021	1971–1994	1971–2009	1971–2015	1971–2021	1994–2009	1994–2015	1994–2021	2009–2015	2009–2021	2015–2021
Carbon	2.7	-4.5	-5.2	-13.5	-16.7	-18.7	-7.1	-7.7	-15.8	-18.9	-20.9	-0.6	-9.4	-12.7	-14.8	-8.8	-12.1	-14.3	-3.6	-6.0	-2.4
Columbia Crest	-77.9	-28.9	-48.7	-74.7	-54.7	-57.4	220.9	131.8	14.4	104.6	92.2	-27.8	-64.3	-36.2	-40.1	-50.6	-11.7	-17.1	78.8	67.9	-6.1
Cowlitz-Ingraham	26.0	-10.9	-10.0	-20.2	-39.1	-43.4	-29.3	-28.5	-36.6	-51.7	-55.1	1.0	-10.4	-31.7	-36.5	-11.4	-32.4	-37.1	-23.7	-29.1	-7.0
Edmunds	-56.6	-58.8	-61.0	-65.3	-67.0	-70.1	-5.0	-10.0	-20.0	-23.9	-31.1	-5.2	-15.7	-19.9	-27.5	-11.1	-15.5	-23.5	-5.0	-14.0	-9.5
Emmons	-35.8	-45.8	-45.4	-47.0	-46.6	-47.1	-15.5	-14.8	-17.4	-16.9	-17.6	0.8	-2.2	-1.6	-2.4	-3.0	-2.4	-3.2	0.6	-0.2	-0.8
Flett	---	---	---	---	---	---	-28.5	-21.8	-27.6	-55.8	-62.0	9.4	1.3	-38.2	-46.9	-7.3	-43.5	-51.4	-39.0	-47.6	-14.1
Fryingpan	97.3	23.3	19.1	-15.3	-17.1	-25.7	-37.5	-39.6	-57.1	-58.0	-62.4	-3.4	-31.3	-32.8	-39.8	-28.9	-30.4	-37.7	-2.2	-12.4	-10.4
Inter	158.9	68.7	65.9	23.5	0.9	-8.9	-34.8	-35.9	-52.3	-61.0	-64.8	-1.7	-26.8	-40.2	-46.0	-25.6	-39.2	-45.1	-18.3	-26.2	-9.8
Kautz-Success	-60.4	-66.3	-75.5	-70.4	-76.4	-78.0	-15.1	-38.3	-25.3	-40.5	-44.4	-27.3	-12.0	-30.0	-34.5	21.0	-3.6	-9.9	-20.4	-25.6	-6.6
Liberty Cap	-19.9	-34.2	-33.2	-28.9	-31.6	-34.3	-17.9	-16.6	-11.3	-14.6	-18.1	1.5	8.0	3.9	-0.2	6.4	2.4	-1.7	-3.8	-7.6	-4.0
Muir	10.2	-19.3	-18.3	-24.7	-29.6	-35.4	-26.8	-25.9	-31.7	-36.2	-41.4	1.3	-6.7	-12.8	-19.9	-7.9	-13.9	-20.9	-6.6	-14.2	-8.1
Nisqually-Wilson	-43.7	-49.6	-47.6	-50.4	-61.0	-62.6	-10.6	-6.9	-11.9	-30.7	-33.6	4.1	-1.5	-22.5	-25.8	-5.4	-25.5	-28.7	-21.2	-24.6	-4.2
North Mowich	-35.5	-54.1	-55.7	-64.4	-64.9	-67.1	-28.9	-31.2	-44.7	-45.6	-49.0	-3.3	-22.3	-23.5	-28.3	-19.6	-20.9	-25.9	-1.6	-7.8	-6.3
Ohanapecosh	---	---	---	---	---	---	-65.2	-64.6	-83.7	-86.9	-88.3	1.9	-53.2	-62.4	-66.5	-54.1	-63.1	-67.1	-19.7	-28.3	-10.7
Paradise-Stevens	-43.9	-82.4	-82.9	-92.8	-94.0	-94.5	-68.7	-69.5	-87.1	-89.3	-90.2	-2.6	-58.8	-65.9	-68.9	-57.7	-65.0	-68.0	-17.4	-24.5	-8.6
Puyallup	-48.5	-60.2	-59.8	-69.9	-72.9	-74.7	-22.8	-22.0	-41.6	-47.4	-50.9	1.0	-24.4	-31.9	-36.5	-25.1	-32.6	-37.1	-10.0	-16.0	-6.7
Pyramid	-60.4	-84.3	-86.2	-93.3	-96.0	-97.7	-60.3	-65.2	-83.2	-89.8	-94.1	-12.2	-57.6	-74.4	-85.1	-51.7	-70.8	-83.1	-39.5	-64.9	-42.0
Russell	-33.3	-56.8	-55.7	-69.2	-67.6	-70.5	-35.2	-33.6	-53.8	-51.5	-55.7	2.4	-28.7	-25.1	-31.6	-30.4	-26.9	-33.2	5.1	-4.1	-8.7
Sarvent	---	---	---	---	---	---	-50.5	-94.1	-49.6	-71.8	-77.9	-88.0	1.7	-43.0	-55.4	746.7	374.1	271.5	-44.0	-56.1	-21.6
South Mowich	-15.8	-30.4	-31.1	-33.3	-37.8	-40.9	-17.3	-18.1	-20.8	-26.1	-29.9	-1.0	-4.3	-10.7	-15.2	-3.3	-9.8	-14.3	-6.7	-11.4	-5.0
South Tahoma	-52.7	-62.0	-73.7	-74.1	-77.4	-78.2	-19.6	-44.4	-45.3	-52.1	-53.9	-30.8	-31.9	-40.4	-42.6	-1.6	-13.9	-17.1	-12.4	-15.7	-3.7
Tahoma	-30.8	-46.3	-49.5	-54.2	-54.1	-57.4	-22.4	-27.1	-33.9	-33.7	-38.4	-6.0	-14.8	-14.6	-20.7	-9.3	-9.2	-15.6	0.2	-6.9	-7.1
Van Trump	-3.4	-64.0	-60.9	-87.3	-94.3	-96.8	-62.7	-59.5	-86.9	-94.2	-96.7	8.8	-64.8	-84.3	-91.0	-67.6	-85.6	-91.8	-55.4	-74.5	-42.9
Whitman	33.0	17.8	24.3	8.9	-2.5	-8.8	-11.4	-6.5	-18.1	-26.7	-31.5	5.5	-7.6	-17.2	-22.6	-12.4	-21.6	-26.7	-10.4	-16.3	-6.5
Winthrop	33.7	23.9	29.4	-3.6	12.5	7.6	-7.3	-3.2	-27.9	-15.8	-19.5	4.5	-22.2	-9.2	-13.1	-25.5	-13.1	-16.9	16.8	11.7	-4.4
Total Change:	**-20.6**	**-37.7**	**-38.5**	**-46.4**	**-49.1**	**-51.6**	**-21.4**	**-22.5**	**-32.5**	**-35.9**	**-39.0**	**-1.4**	**-14.0**	**-18.4**	**-22.3**	**-12.8**	**-17.3**	**-21.2**	**-5.1**	**-9.6**	**-4.7**
Years:	**17**	**75**	**98**	**113**	**119**	**125**	**58**	**81**	**96**	**102**	**108**	**23**	**38**	**44**	**50**	**15**	**21**	**27**	**6**	**12**	**6**
Avg. Change:	**-1.21**	**-0.50**	**-0.39**	**-0.41**	**-0.41**	**-0.41**	**-0.37**	**-0.28**	**-0.34**	**-0.35**	**-0.36**	**-0.06**	**-0.37**	**-0.42**	**-0.45**	**-0.86**	**-0.82**	**-0.79**	**-0.85**	**-0.80**	**-0.79**

The fact that the glacial volume calculated in this study falls within the volumetric changes defined by Sisson and others (2011) and measured in this study provides some confidence that the volume-area method we used (Equation 11) produces favorable results within a margin of error. Therefore, we have a higher confidence in the estimates of total glacial volume over the last 125 years at the Park, within the margin of error, presented here.

Figure 18 and Table 18 show the change in volume of glaciers by aspect at Mount Rainier. North and south aspect glaciers are defined in Section 5.3.3.

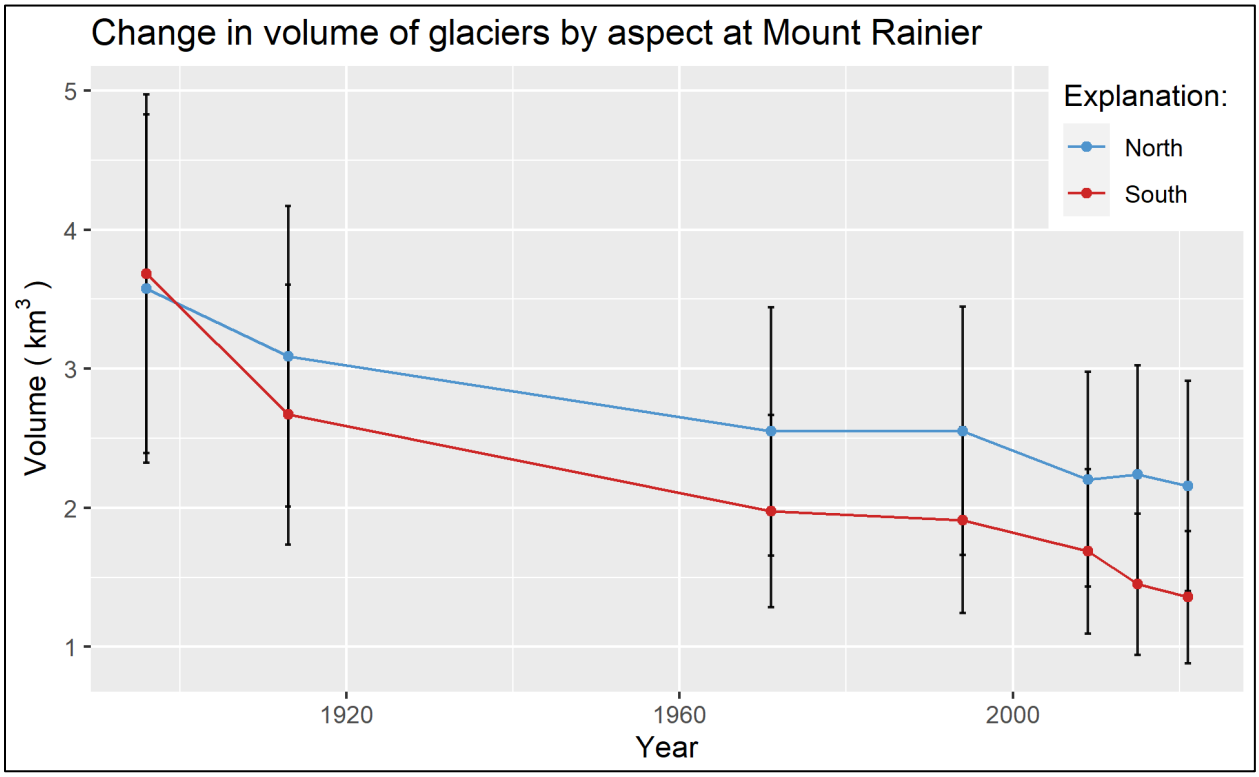


Figure 18. Change in volume of glaciers by aspect from 1896 to 2021 at Mount Rainier, based on data from Table 18.

Table 18. Changes in volume of glaciers by aspect at Mount Rainier for various time periods. Listed units are in cubic kilometers (km^3). Values are based on volumes from Table 15.

Aspect	1896	1913	1971	1994	2009	2015	2021	1896–2021 Change	1896–2021 Change (%)
North[1]	3.58	3.09	2.55	2.55	2.20	2.24	2.16	-1.42	-39.7
South[1]	3.68	2.67	1.98	1.91	1.69	1.45	1.36	-2.32	-63.1

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

In a similar trend observed in Figure 10 and Table 10 (areas), south facing glaciers are losing more glacial ice than their north-facing counterparts. South facing glaciers had a more rapid loss of volume from 1896 to 2021 of -2.32 km^3 (0.56 mi^3) compared to -1.42 km^3 (0.34 mi^3) (1.63 times the loss of

the north extent). This corresponds to an average annual loss (over 125 years) of 0.019 km^3 per year (0.005 $mi^3 \times yr^{-1}$) for the south and 0.011 km^2 per year (0.003 $mi^3 \times yr^{-1}$) for the north aspect glaciers in 125 years.

5.8. Recommendations for Future Work

Understanding the interactions between retreating glaciers and their associated ecosystems are one of the key benefits of these kind of surveys. We recommend developing updated glacial extents layers every five to 10 years, especially as more frequent digital elevation data becomes available (e.g., satellite and fixed-wing SfM surveys and updated LiDAR datasets). Digital elevation data is a primary source of volumetric change in various timeframes and the only real source of high-resolution and high-accuracy volume changes in the Park.

Total glacial volume in each survey period were estimated in this work and calibrated to a single estimate of glacial mass from glacial extents in 1971 and measurements of subglacial topography measured in the early 1980s Driedger and Kennard (1986). Given that four to five decades have passed since the work by Driedger and Kennard (1986), a new comprehensive look at the glacial volume of Mount Rainier and other Cascade Volcanoes is sorely needed. Despite having a good idea of volumetric changes in glacial ice between 1971-2007/8 and 2007/8-2021, we still lack low-error values for glacial volume at specific times during the last 125 years. Notwithstanding the caveats for volume estimates, the data presented here are still quite useful as a method of understanding not only how glacial ice is decreasing in area, but also how it is decreasing from the “top down”. This area of study would benefit a wide variety of work in aquatic, geomorphic, and geohazard recognition for a wide-ranging audience.

6. Conclusions

Glaciers are an important and complex cryospheric feature whose health is balanced between winter accumulation and summer melt. They serve as a significant source of ice at Mount Rainier which provides cool water in summer months to a variety of ecosystems. They also serve as the architects of Mount Rainier, sculpting the lava flows during periods of volcanic unrest and continuously wearing down the volcano during periods of volcanic quiescence. Glaciers are one of the best indicators of climate change in a region since their surface features, extent, and volume all respond to the long-term balances of accumulation and ablation of snow.

With the exception of some periods in the 1960s to 1980s, glaciers at MORA have been in an overall retreat since the late 1800s. The implications of this retreat are widespread, affecting everything from aquatic organisms to the fluvial geomorphology of proglacial braided rivers. Damaging outburst floods unleashed by glaciers and the voluminous sediment left behind by retreating glaciers have led to scores of debris flows at MORA, which has led to changes in Park management in large swaths of land throughout MORA.

Studying the long-term trends at Mount Rainier glaciers reveals important insights into the health of Park glaciers and provides key data to regional glacier studies. These studies complement each other and provide a look at the glacial loss in the Cascade Range. Loss of glacial area and associated volume loss of glacial ice throughout the Cascades represents a significant loss of freshwater resources in the region, which can have compounding ecologic and geomorphic effects.

Technology like SfM has allowed a tremendous new opportunity to capture extremely large amounts of data quickly and inexpensively. This photographic and digital elevation data serve as the basis for the 2021 glacial update at MORA and will allow for future high-resolution surveys to monitor the glacial resources at the Park.

All 28 glaciers at Mount Rainier are in retreat, losing an average of -0.430 km^2 per year (-0.166 $mi^2 \times yr^{-1}$) parkwide during the last 125 years. Since 2015, this rate has increased to -0.544 km^2 per year (-0.210 $mi^2 \times yr^{-1}$) parkwide. When looking at volumetric data, the Park has lost a total of -1.057 km^3 (-0.254 mi^3) of glacial mass since 1970, at a rate of about -0.021 km^3 per year (-0.005 $mi^2 \times yr^{-1}$). As of 2021, the Park contains 75.496 ± 4.109 km^2 (29.149 ± 1.587 mi^2) and about 3.516 ± 1.231 km^3 (0.844 ± 0.295 mi^3) of glacial ice.

This survey removes the Stevens Glacier from the Park's glacier inventory. The Stevens Glacier has been languishing for decades in a south-facing, low elevation location that is physically detached from a higher accumulation zone. While it may still serve as a perennial snowfield, it no longer contributes to the Park's glacier inventory. Two other south-facing glaciers at Mount Rainier are in a significantly perilous state. The Pyramid and Van Trump glaciers lost 32.9% and 33.6% of their area and 42.0% and 42.9% of their volume in the last six years, respectively, and have become exceedingly fragmented. These glaciers may only have a few decades left being listed on the Park's glacier inventory if climate trends do not change.

The glaciers at Mount Rainier are in a long-term demise. Our data shows a gradual yet accelerating loss of glacial ice at Mount Rainier, resulting in significant changes in regional ice volume over the last century. The long-term impacts of this loss will be widespread and impact many facets of the Park ecosystem. Additionally, rapidly retreating south-facing glaciers are exposing vast sources of loose sediment that can be provided to proglacial rivers during warm rainstorms, outburst floods, and debris flows. Monitoring the glacial and proglacial resources at MORA over the next century will be key to understanding the long-term impacts of loss of glacial ice to the management of the Park and effects to the region.

7. Data Availability

The 2021 glacier extents GIS layers for MORA are available from the Park or through the National Park Service Integrated Resource Management Application (IRMA) Data Store website at: https://irma.nps.gov/DataStore/Reference/Profile/2298869.

Literature Cited

Bahr, D.B., M.F. Meier, and S.D. Peckham. 1997. The physical basis of glacier volume-area scaling. Journal of Geophysical Research, B, Solid Earth and Planets, Vol. 102, p. 20,355-20,362, doi: 10.1029/97JB01696.

Bahr, D.B., W.T. Pfeffer, C. Sassolas, and M.F. Meier. 1998. Response time of glaciers as a function of size and mass balance: 1. Theory. Journal of Geophysical Research, Vol. 103, No. B5, p. 9,777-9,782, doi: 10.1029/98JB00507.

Bahr, D.B., W.T. Pfeffer, and G. Kaser. 2015. A review of volume-area scaling of glaciers. Reviews of Geophysics, Vol. 53, No. 1, p. 95-140, doi: 10.1002/2014RG000470.

Basehart, A., S. Altenberger, M. Koutnik, and C. Todd. 2017. Mapping supraglacial debris on Emmons Glacier, Mount Rainier, WA. Poster 158-3, Geological Society of America Abstracts with Programs, Vol. 49, No. 6, doi: 10.1130/abs/2017AM-307852.

Bates, R.L. and J.A. Jackson, editors. 1984. Dictionary of geological terms, 3rd edition. Anchor Books, New York, NY, 571 p.

Beason, S.R. 2017. Change in glacial extent at Mount Rainier National Park from 1896-2015. National Park Service Natural Resource Report NPS/MORA/NRR-2017/1472. 98 p.

Beason, S.R. and T.R. Kenyon. 2018. Time-lapse photography of glaciers at Mount Rainier National Park [Online]. National Park Service Resource Article. Retrieved from https://www.nps.gov/articles/time-lapse-photography-of-glaciers-at-mount-rainier.htm.

Beason, S.R., N.T. Legg, T.R. Kenyon, and R.P. Jost. 2021. Forecasting and seismic detection of proglacial debris flows at Mount Rainier National Park, Washington, USA. Environmental and Engineering Geoscience, Vol. 27, No. 1, pp. 57-72, doi: 10.2113/EEG-D-20-00014.

Carisio, S.P. 2012. Evaluating areal errors in Northern Cascade Glacier inventories. M.S. Geography Thesis, University of Delaware. 71 p.

Chen, J. and A. Ohmura. 1990. Estimation of alpine glacier water resources and their change since the 1870s. IAHS Publications, Vol. 193, p. 127-135.

Cogley, J.G., R. Hock, L.A. Rasmussen, A.A. Arendt, A. Bauder, R.J. Braithwaite, P. Jansson, G. Kaser, M. Möller, L. Nicholson, and M. Zemp. 2011. Glossary of glacier mass balance and related terms. IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris, 114 p.

Copeland, E.A. 2009. Recent periglacial debris flows from Mount Rainier, Washington. M.S. Water Resource Engineering Thesis. Oregon State University, Corvallis, Oregon, 125 p.

Crandell, D.R. 1971. Postglacial lahars from Mount Rainier Volcano, Washington. United States Geological Survey Professional Paper 677, 75 p., doi: 10.313/pp677.

Crandell, D.R. and R.K. Fahnestock. 1965. Rockfalls and avalanches from Little Tahoma Peak on Mount Rainier, Washington. U.S. Geological Survey Bulletin 1221-A, 30 p, doi: 10.3133/b1221A.

Cuffey, K. and W.S.B. Paterson. 2006. The physics of glaciers, 4th edition. Academic Press, 704 p.

De La Fuente, J.A., S. Bachman, A. Courtney, N. Myers, R. Mikulovsky, B. Rust, F. Coots, and D. Viech. The debris flow of September 20, 2014, in Mud Creek, Mount Shasta Volcano, Northern California. Abstract NH41C-1839, American Geophysical Union Fall Meeting 2015, San Francisco, CA.

DeVisser, M.H. and A.G. Fountain. 2015. A century of glacier change in the Wind River Range, Wyoming. Geomorphology, Vol. 232, p. 103-116, doi: 10.1016/j.geomorph.2014.10.017.

Dick, K.A. 2013. Glacier change in the North Cascades, Washington: 1900-2009. M.S. Geography Thesis, Portland State University. 130 p.

DigitalGlobe. 2016. Accuracy of Worldview products [Online]. DigitalGlobe white paper. Retrieved from: https://dg-cms-uploads-production.s3.amazonaws.com/uploads/document/file/38/DG_ACCURACY_WP_V3.pdf

Dits, T. and P. Moore. 2013. Small-scale variations in melt of a debris-covered glacier: Emmons Glacier, Mount Rainier National Park. National Park Service Science Brief, 3 p.

Driedger, C.L. 1993. Glaciers on Mount Rainier [Online]. U.S. Geological Survey Open-File Report 92-474. Retrieved from: http://wa.water.usgs.gov/pubs/fs/fs_rainier.html.

Driedger, C.L. and P.M. Kennard. 1986. Ice volumes on Cascade Volcanoes: Mount Rainier, Mount Hood, Three Sisters, and Mount Shasta. United States Geological Survey Professional Paper 1365, 28 p, doi: 10.3133/pp1365.

Driedger, C.L. and A.G. Fountain. 1989. Glacier outburst floods at Mount Rainier, Washington State, U.S.A. Annals of Glaciology, Vol. 13, p. 51-55, doi: 10.3189/S0260305500007631.

Driedger, C.L. and J.S. Walder. 1991. Recent debris flows at Mount Rainier. United States Geological Survey Open-File Report 91-242. 2 p.

Eckert, A. 2011. NAIP horizontal accuracy specification [Online]. Presentation to USAD Imagery Planning and Coordination Meeting, December 6-8, 2011. Retrieved from: https://www.fsa.usda.gov/Internet/FSA_File/pm2011_aaroneckert_accuracy.pdf

Ellinger, J.R. 2010. The changing glaciers of Mt. Hood, Oregon and Mt. Rainier, Washington: Implications for periglacial debris flows. M.S. Geography Thesis, Oregon State University, 146 p.

ESRI. 2016. An overview of the Hydrology toolset [Online]. Retrieved from: http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/an-overview-of-the-hydrology-tools.htm.

Ewert, J.W., A.K. Diefenbach, and D.W. Ramsey. 2018. 2018 update to the U.S. Geological Survey national volcanic threat assessment. United States Geological Survey Scientific Investigations Report 2018-5140, 40 p., doi: 10.3133/sir20185140.

Fontana, B., C. Todd, M. Koutnik, B. Flury, L. Black, and L. Krehbiel. 2021. Surface elevation change on debris-covered Emmons Glacier, Mount Rainier, WA. Poster 117-5, Geological Society of America Abstracts with Programs, Vol. 53, No. 6, doi: 10.1130/abs/2021AM-370335.

Fordham, E.M. 2022. Glacier Peak and the chocolate factory: Recurring debris flows from the eastern flank of Glacier Peak stratovolcano, North Cascades, Washington State, USA. M.S. Geology Thesis, Western Washington University, 111 p.

Fountain, A.G., B. Glenn, and H.J. Basagic. 2017. The geography of glaciers and perennial snowfields in the American West. Artic, Antarctic, and Alpine Research, Vol. 49, No. 3, p. 391-410, doi: 10.1657/AAAR0017-003.

Fountain, A.G., C. Gray, B. Glenn, B. Menounos, J. Pflug, and J.R. Riedel. 2022. Glaciers of the Olympic Mountains, Washington – The past and future 100 years. Journal of Geophysical Research Earth Surface, Vol. 27, No. 4, doi: 10.1029/2022JF006670.

Frans, C., E. Istanbulluoglu, D.P. Lettenmaier, A.G. Fountain, and J.L. Riedel. 2018. Glacier recession and the response of summer streamflow in the Pacific Northwest United States, 1960-2099. Water Resources Research, Vol. 54, No. 9, p. 6202-6225, doi: 10.1029/2017WR021764.

George, J.L. and S.R. Beason. 2017. Dramatic changes to glacial volume and extent since the late 19th century at Mount Rainier National Park, Washington, USA. Poster #158-6, Geological Society of America Abstracts with Programs, Vol. 49, No. 6, doi: 10.1130/abs/2017AM-299694.

Granshaw, F.D. and A.G. Fountain. 2006. Glacier change (1958-1998) in the North Cascades National Park complex, Washington, USA. Journal of Glaciology, Vol. 52, No. 177, p. 251-256, doi: 10.3189/172756506781828782.

Headman, A., E.N. Whorton, D.E. Shean, and E. McCann. 2017. A semi-automated methodology for using historical aerial photography to create high-resolution elevation and orthoimagery products of South Cascade Glacier, Washington, USA. Presentation 23-6, Geological Society of America Abstracts with Programs, Vol. 49, No. 6, doi: 10.1130/abs/2017AM-307152.

Heliker, C.C., A. Johnson, and S.M. Hodge. 1983. The Nisqually Glacier, Mount Rainier, Washington, 1857-1979: A summary of long-term observations and a comprehensive bibliography. U.S. Geological Survey Open-File Report 84-541. 20 p, doi: 10.3133/ofr83541.

Hoblitt, R.P., J.S. Walder, C.L. Driedger, K.M. Scott, P.T. Pringle, and J.W. Vallance. 1998. Volcano hazards from Mount Rainier, Washington: Revised 1998. U.S. Geological Survey Open File Report 98-428, doi: 10.3133/ofr98428.

Hodge, S.M. 1974. Variations in the sliding of a temperate glacier. Journal of Glaciology, Vol. 13, No. 69, p. 349-369, doi: 10.3189/S0022143000023157.

Hoffman, R.L., A. Woodward, P. Haggarty, K. Jenkins, P. Griffin, M.J. Adams, J. Hagar, T. Cummings, D. Duriscoe, K. Kopper, J. Riedel, B. Samora, L. Marin, G.S. Mauger, K. Bumbaco, and J.S. Littell. 2014. Mount Rainier National Park: Natural Resource Condition Assessment. National Park Service Natural Resource Report NPS/MORA/NRR—2014/894. 350 p.

Hooke, R.L. 2020. Principles of glacier mechanics, 3rd edition. Cambridge University Press, Cambridge, UK, 618 p.

Ireson, R., C. Todd, and M. Koutnik. 2021. Evolution of debris cover on Emmons Glacier, Mount Rainier, Washington. Poster 117-3, Geological Society of America Abstracts with Programs, Vol. 53, No. 6, doi: 10.1130/abs/2021AM-369901.

King, C. On the discovery of actual glaciers on the mountains of the Pacific slope. The American Journal of Science and Arts – Third Series, Vol. 1, No. 3, p. 157-167.

Lancaster, S.T., A.W. Nolin, E.A. Copeland, and G.E. Grant. 2012. Periglacial debris-flow initiation and susceptibility and glacial recession from imagery, airborne LiDAR, and ground-based mapping. Geosphere, Vol. 8, No. 2., p. 417-430, doi: 10.1130/GES00713.1.

Lescinsky, D.T. and T.W. Sisson. 1998. Ridge-forming, ice-bounded lava flows at Mount Rainier, Washington. Geology, Vol. 26, No. 4, p. 351-354, doi: 10.1130/0091-7613(1998)026<0351:RFIBLF>2.3.CO;2.

Matthes, F. 1914. Mount Rainier and its Glaciers. Mount Rainier National Park, U.S. Government Printing office, 48 p.

Medley, B. 2008. A method for remotely monitoring glaciers with regional application to the Pacific Northwest. M.S. Thesis, Oregon State University, Corvallis, OR, 85 p.

Meier, M.F. 1998. Land ice on Earth: A beginning of a global synthesis. American Geophysical Union, 19 p.

Mikulovsky, R.P., J.A. De La Fuente, A. Courtney, S. Bachmann, H. Rodriguez, B. Rust, F. Schneider, and D. Veich. Rainfall generated debris flows on Mount Shasta: July 21, 2015. Abstract H51E-1414, American Geophysical Union Fall Meeting 2015, San Francisco, CA.

Moore, P.L., L.I. Nelson and T.M. Dits. 2014. Melting the rocky terminus of Emmons Glacier. Unpublished Science Brief, Mount Rainier National Park, Ashford, WA, 2 p.

Moore, P.L., L.I. Nelson, and T.M. Growth. 2019. Debris properties and mass-balance inputs on adjacent debris-covered glaciers, Mount Rainier, USA. Arctic, Antarctic, and Alpine Research, Vol. 51, No. 1, p. 70-83, doi: 10.1080/15230430.2019.1582269.National Park Service. 2014. North Coast and Cascades Network (NCCN) Monitoring [Online]. Retrieved from http://science.nature.nps.gov/im/units/nccn/monitor/index.cfm.

National Park Service. 1931. The Williwakas Slide [Online]. Mount Rainer National Park Nature Notes, July 1, 1931, Vol. IX, No. 5. Retrieved from: http://npshistory.com/nature_notes/mora/vol9/vol9-5-2a.htm.

National Park Service. 1989. Ice Caves [Online]. Mount Rainier National Park Nature Notes, January-May 1989, Vol. III, No. 1. Retrieved from: http://npshistory.com/nature_notes/mora/vol3a/vol3a-1b.htm.

National Park Service. 2012. Glaciers – North Cascades, Mount Rainier: I&M Resource Brief [Online]. Retrieved from: http://science.nature.nps.gov/im/units/nccn/assets/docs/briefs/2012-glaciers.pdf.

Neiman, P.J., F.M. Ralph, G.A. Wick, Y-H Kuo, T-K Wee, Z. Ma, G.H. Taylor, and M.D. Dettinger. 2008. Diagnosis of an intense atmospheric river impacting the Pacific Northwest: Storm summary and offshore vertical structure observed with COSMIC satellite retrievals. American Meteorological Society Monthly Water Review, Vol. 136, p. 4398-4420, doi: 10.1175/2008MWR2550.1.

Neiman, P.J., L.J. Schick, F.M. Ralph, M. Hughes, and G.A. Wick. 2011. Flooding in Western Washington: The connection to atmospheric rivers. Journal of Hydrometerology, Vol. 12, p. 1337-1358, doi: 10.1175/2011JHM1351.1.

Nylen, T.H. 2001. Spatial and temporal variations of glaciers (1913-1994) on Mt. Rainier and the Relation with Climate. M.S. Thesis. Portland State University, Portland, Oregon, 128 p.

Pelto, M.S. 2008. Impact of climate change on North Cascades alpine glaciers, and alpine runoff. Northwest Science, Vol. 82, No. 1, p. 65-75.

Pelto, M. 2015. Climate driven retreat of Mount Baker glaciers and changing water resources. Springer International Printing. 107 p.

Pelto, M. 2017. How unusual was 2015 in the 1984-2015 period of the North Cascade annual mass balance? Water, Vol. 10, No. 5, 15 p., doi: 10.3390/w10050543.

Post, A., D. Richardson, W.V. Tangburn, and F.L Rosselot. 1971. Inventory of glaciers in the North Cascades, Washington. U.S. Geological Survey Professional Paper 705-A. 19 p, doi: 10.3133/pp705A.

Radić, V., R. Hock, and J. Oerlemans. 2017. Analysis of scaling methods in deriving future volume estimations of valley glaciers. Journal of Glaciology, Vol. 54, No. 187, p. 601-612, doi: 10.3189/002214308786570809.

Riedel, J.L. and M.A. Larrabee. 2015. Mount Rainier National Park glacier mass balance monitoring annual report, water year 2011: North Coast and Cascades Network. Natural Resource Data Series NPS/NCCN/NRDS—2015/752. National Park Service, Fort Collins, Colorado.

Riedel, J.L. and M.A. Larrabee. 2016. Impact of recent glacial recession on summer streamflow in the Skagit River. Northwest Science, Vol. 90, No. 1, p. 5-22.

Riedel, J.L., S. Wilson, W. Baccus, M. Larrabee, and T.J. Fudge. 2015. Glacier status and contribution to streamflow in the Olympic Mountains, USA. Journal of Glaciology, Vol. 61, No. 225, 9 p., doi: 10.3189/2015JoG14J138.

Riedel, J.L., J.M. Wenger, and N.D. Bowerman. 2010. Long term monitoring of glaciers at Mount Rainier National Park: Narrative and standard operating procedures version 1.0. Natural Resource Report NPS/NCCN/NRR—2010/175. National Park Service, Fort Collins, Colorado.

Robinson, J.E., T.W. Sisson, and D.D. Swinney. 2010. Digital topographic map showing the extents of glacial ice and perennial snowfields at Mount Rainier, Washington, based on the LiDAR survey of September 2007 to October 2008 [Online]. U.S. Geological Survey Data Series 549. Retrieved from http://pubs.usgs.gov/ds/549.

Russell, I.C. 1897. Glaciers of Mount Rainier. Extract from the eighteenth annual report of the U.S. Geological Survey, 1896-1897: Part II – Papers chiefly of a theoretic nature. p. 349-423.

Scott, K.M. and J.W. Vallance. 1995. Debris flow, debris avalanche and flood hazards at and downstream from Mount Rainier, Washington. United States Geological Survey Hydrologic Atlas 729, 9 p., doi: 10.3133/ha729.

Scott, K.M., J.W. Vallance, and P.T. Pringle. 1995. Sedimentology, behavior, and hazards of debris flows at Mount Rainier, Washington. United States Geological Survey Professional Paper 1547, 56 p., doi: 10.3133/pp1547.

Shean, D.E., O. Alexandrov, Z.M. Moratto, B.E. Smith, I.R. Joughin, C. Porter, and P. Morin. 2016. An automated, open-source pipeline for mass production of digital elevation model (DEMs) from very-high-resolution commercial stereo satellite imagery. ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 116, p. 101-117, doi: 10.1016/j.isprsjprs.2016.03.012.

Shean, D.E. 2017. Using repeat high-res DEMs to quantify mountain glacier mass balance, snow depth, and landslide evolution [Presentation]. USGS Tacoma Seminar Series, Wednesday, March 8, 2017, Tacoma, WA.

Sisson, T.W. and J.W. Vallance. 2009. Frequent eruptions of Mount Rainier over the last ~2,600 years. Bulletin of Volcanology, Vol. 71, No. 6, p. 595-618, doi: 10.1007/s00445-008-0245-7.

Sisson, T.W., J.E. Robinson, and D.D. Swinney. 2011. Whole-edifice ice volume change A.D. 1970-2007/8 at Mount Rainier, Washington, based on LiDAR surveying. Geology, Vol. 39., p. 639-642, doi: 10.1130/G31902.1.

Sitts, D.J., A.G. Fountain, and M.J. Hoffman. 2010. Twentieth century glacier change on Mount Adams, Washington, USA. Northwest Science, Vol. 84, No. 4, p. 378-385.

Skloven-Gill, J. and A.G. Fountain. 2015. Glacier change, kinematic waves, and outburst floods at Nisqually Glacier, Mount Rainier, Washington: Data analysis and review. Unpublished report, Portland State University, 21 p.

Stevens, C.M., H. Conway, P.M. Kennard, L.A. Rasmussen, and M. Koutnik. 2016. Glacier retreat, outburst floods, and kinematic waves: Nisqually Glacier changes related to climate. Unpublished report to Mount Rainier National Park, Department of Earth and Space Sciences, University of Washington, 29 p.

Todd, C., R. Ireson, A. Sheflo, and M. Koutnik. 2021. Evolution of a glacier terminus with implications for locating stagnant ice. Presentation 39-4, Geological Society of America Abstracts with Programs, Vol. 63, No. 6, doi: 10.1130/abs/2021AM-369972.

Todd, C., J. Jimenez, J. Baker, C. Lewarne, B. Fontana, B. Flury, and L. Black. 2022. Field observations of glacier change in Mount Rainier National Park. Presentation 52-4, Geological Society of America Abstracts with Programs, Vol. 54, No. 5, doi: 10.1130/abs/2022AM-383223.

United States Environmental Protection Agency. 2016. Climate change indicators: Glaciers [Online]. Retrieved from: https://www.epa.gov/climate-indicators/climate-change-indicators-glaciers.

United States Geological Survey. 1999. Map accuracy standards. USGS Fact Sheet 171-99, 2 p.

Vallance, J.W., M.L. Cunico, and S.P. Schilling. 2003. Debris-flow hazards caused by hydrologic events at Mount Rainier, Washington. United States Geological Survey Open-File Report 2003-368, 4 p.

Walder, J.S., S.P. Schilling, D.R. Sherrod, and J.W. Vallance. 2010. Photographic documentation of the evolution of Crater Glacier, Mount St. Helens, Washington, September 2006-November 2009. U.S. Geological Survey Open-File Report 2010-1141. 6 p., doi: 10.3133/ofr20101141.

Walder, J.S. and C.L. Driedger. 1994. Geomorphic change caused by outburst floods and debris flows at Mount Rainier, Washington, with emphasis on Tahoma Creek valley. U.S. Geological Survey Water Resources Investigations Report 93-4093, 93 p., doi: 10.3133/wri934093.

Walkup, L.C., P.M. Kennard, J.G. Ohlschlager, and S.R. Beason. 2019. Surficial velocities of the Nisqually Glacier, Mount Rainier National Park, 2011 and 2012. Unpublished Internal Report, Mount Rainier National Park, Ashford, WA, 30 p.

Watershed Sciences, Inc. 2009. LiDAR remote sensing data collection: Mount Rainier, WA, March 25, 2009. Watershed Sciences, Inc., Corvallis, OR, 31 p.

Whorton, E.N., A. Headman, D.E. Shean, and E. McCann. 2017a. A semi-automated approach to derive elevation time-series and calculate glacier mass balance from historical aerial imagery. Abstract C53D-07, American Geophysical Union Fall Meeting 2017, San Francisco, CA.

Whorton, E.N. D.E. Shean, D. Fagre, C. McNeil, A. Clark, L. Saas, A. Headman, E. Peitzsch, D. McGrath, and E.H. Baker. 2017b. Assessing mass balance change at South Cascade Glacier: Is it representative of regional glaciers? Presentation 23-5, Geological Society of America Abstracts with Programs, Vol. 49, No. 6, doi: 10.1130/abs/2017AM-307714.

Wokosin, K.A., P.M. Kennard, and P. Edminston. 2017. Geochemical Monitoring of stagnant ice for glacial outburst flood hazard assessment, Mount Rainier National Park. Presentation 23-11, Geological Society of America Abstracts with Programs, Vol. 49, No. 6, doi: 10.1130/abs/2017AM-301059.

Appendix A: Detail Maps of Individual Named Glaciers at Mount Rainier

Notes for all appendix maps and tables (Figures A-1 through A-29, and Tables A-1 through A-29):

- 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 4.
- Rank and estimated volume of glaciers are from Table 12.

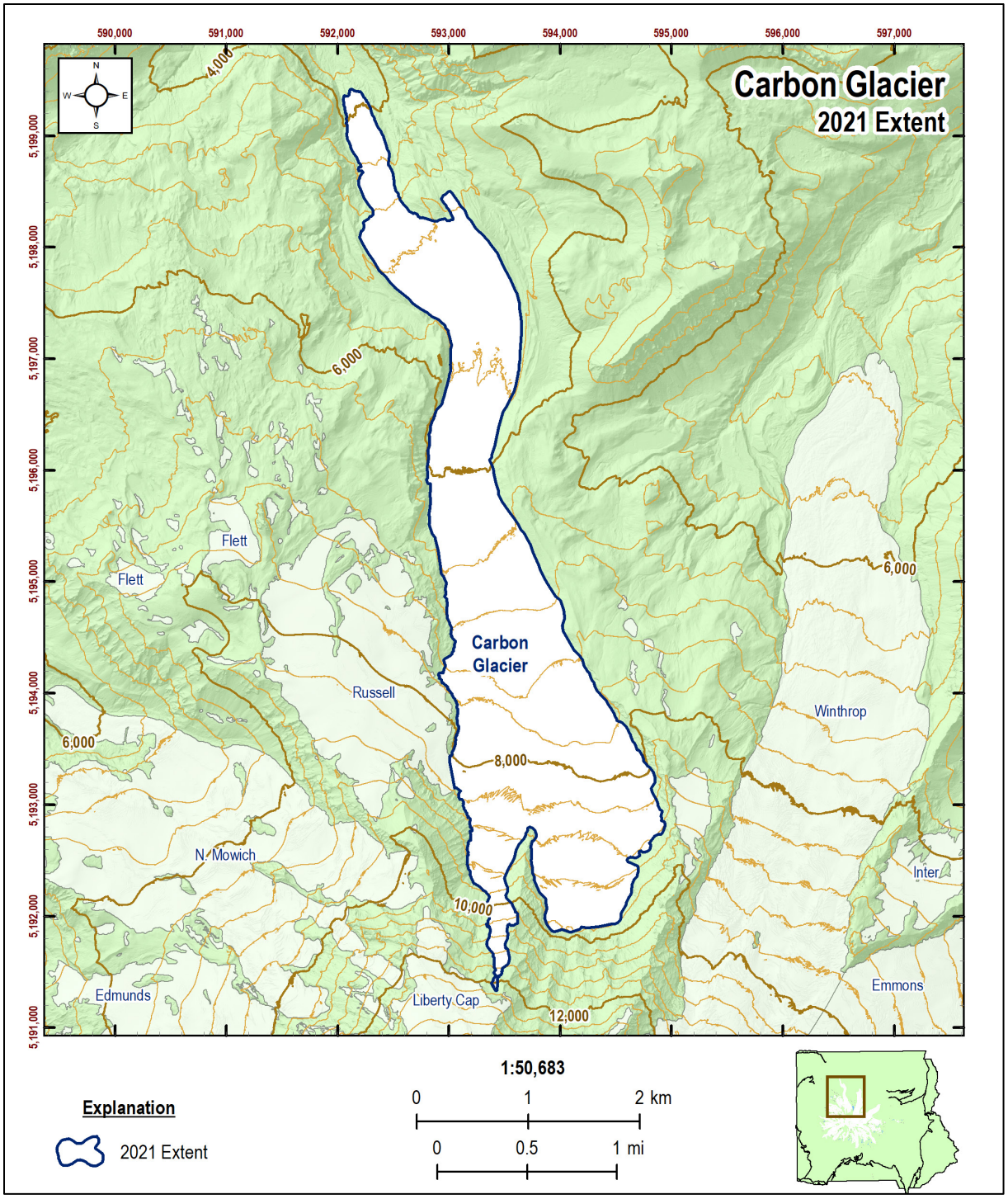


Figure A-1. Year 2021 glacial extent for Carbon Glacier.

Table A-1. Year 2021 glacial extent and estimated volume for Carbon Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Carbon	3	7,127,273	7.127	2.752	2	491,933,794	0.4919	0.1180

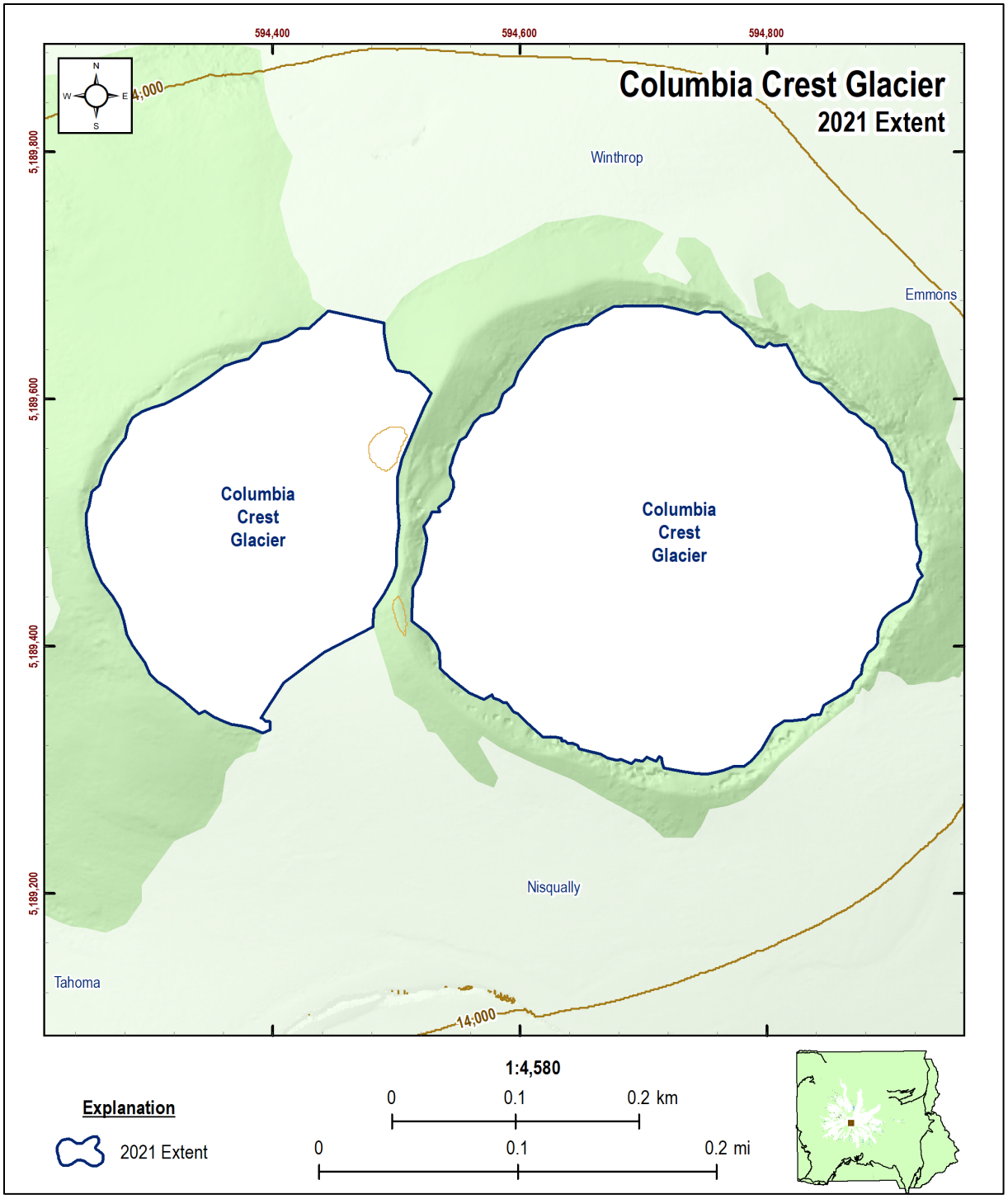


Figure A-2. Year 2021 glacial extent for Columbia Crest Glacier.

Table A-2. Year 2021 glacial extent and estimated volume for Columbia Crest Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Columbia Crest	27	172,250	0.172	0.067	27	2,354,888	0.0024	0.0006

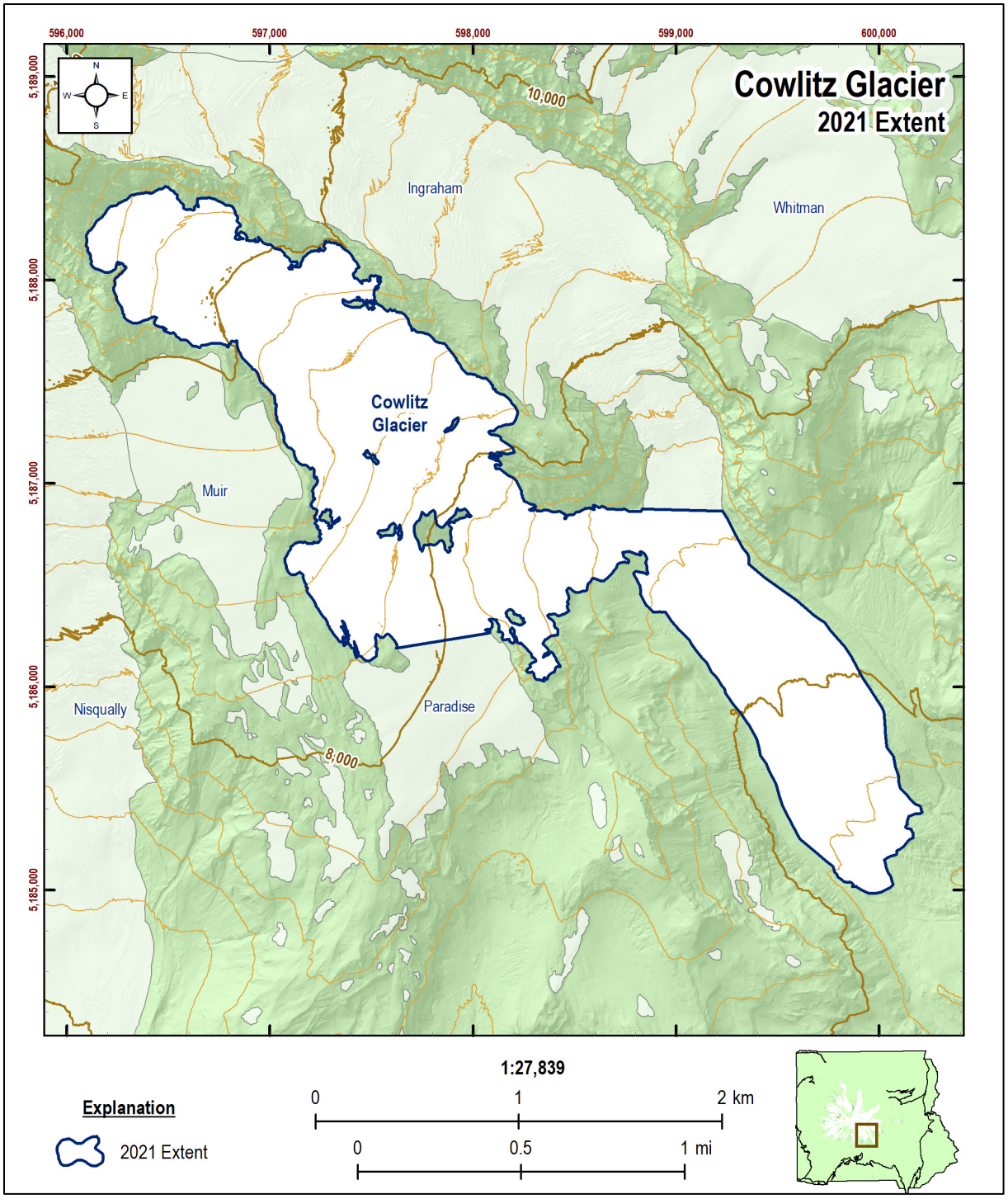


Figure A-3. Year 2021 glacial extent for Cowlitz Glacier.

Table A-3. Year 2021 glacial extent and estimated volume for Cowlitz Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Cowlitz	7	3,684,615	3.685	1.423	7	169,289,501	0.1693	0.0406

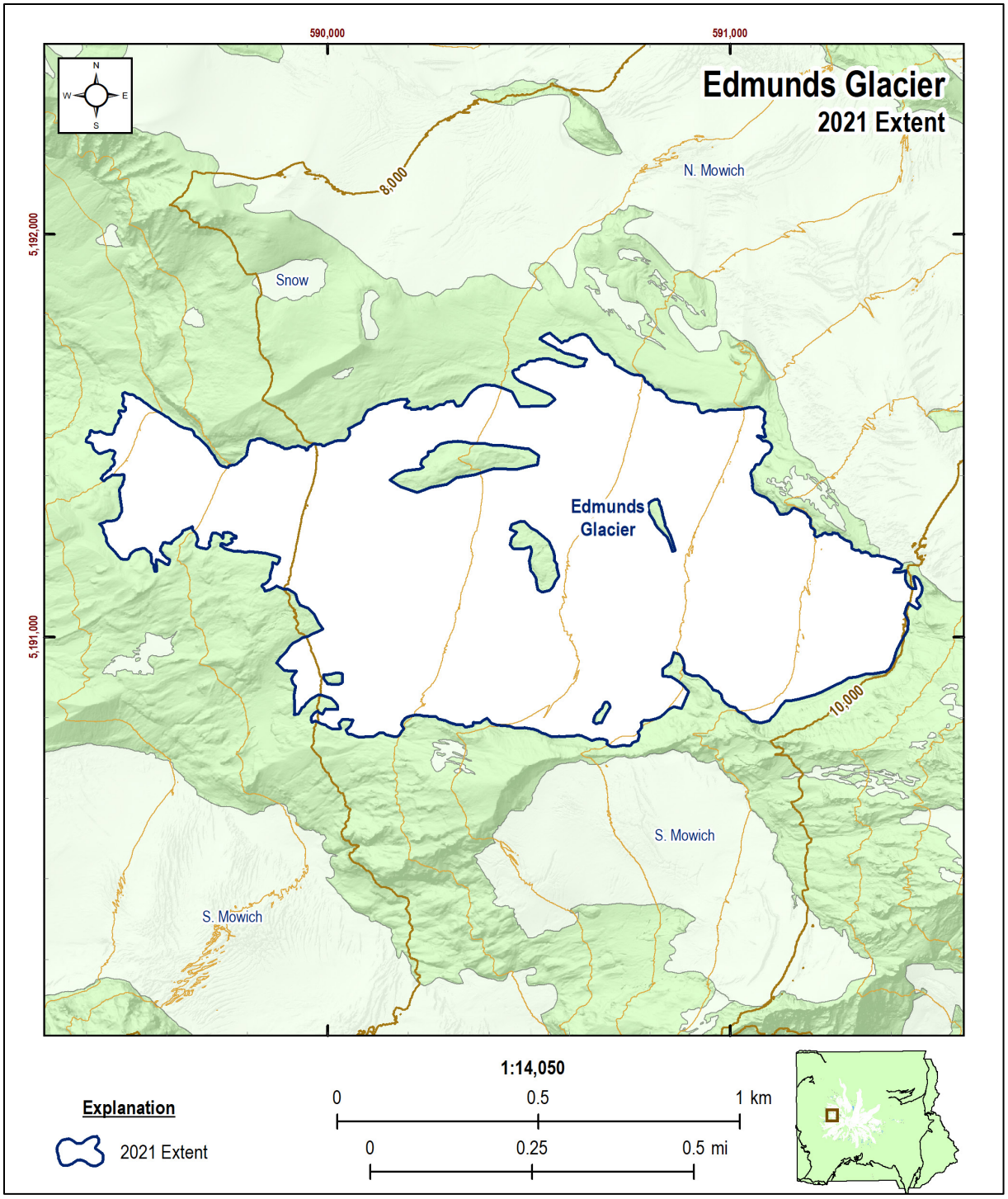


Figure A-4. Year 2021 glacial extent for Edmunds Glacier.

Table A-4. Year 2021 glacial extent and estimated volume for Edmunds Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Edmunds	18	1,164,597	1.165	0.450	18	27,854,541	0.0279	0.0067

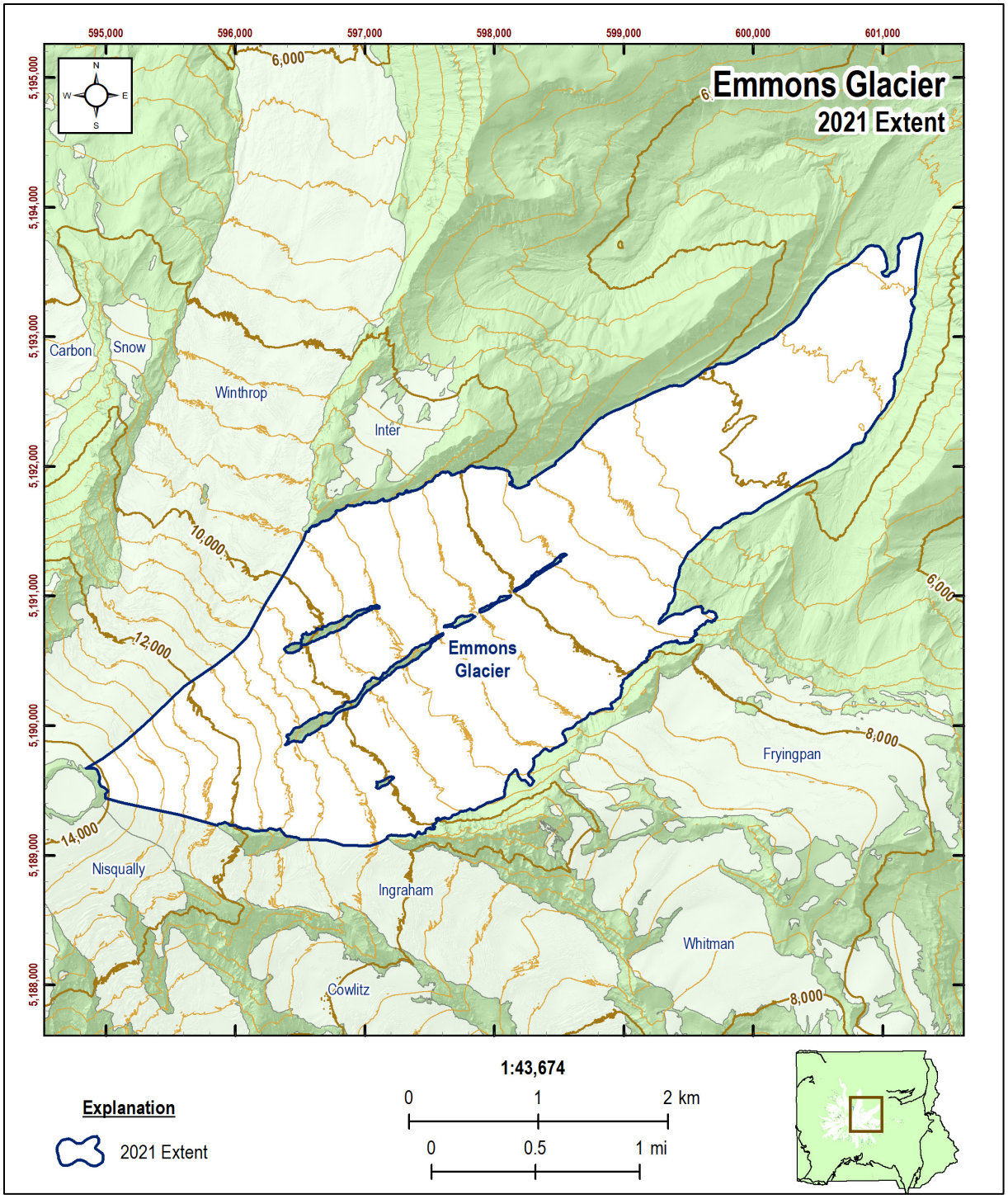


Figure A-5. Year 2021 glacial extent for Emmons Glacier.

Table A-5. Year 2021 glacial extent and estimated volume for Emmons Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Emmons	1	10,959,203	10.959	4.231	1	659,213,186	0.6592	0.1582

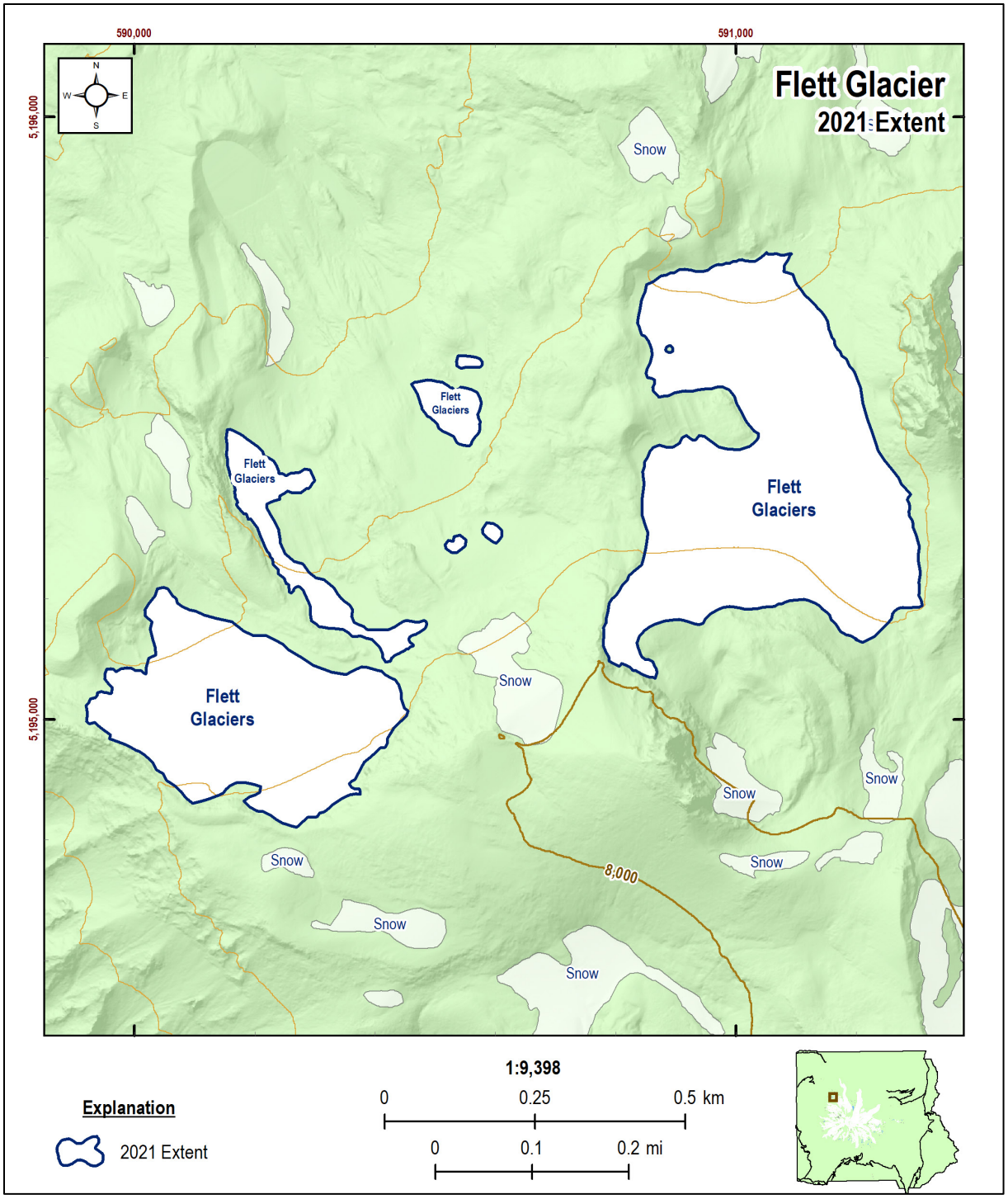


Figure A-6. Year 2021 glacial extent for Flett Glaciers.

Table A-6. Year 2021 glacial extent and estimated volume for Flett Glaciers.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Flett	25	362,938	0.363	0.140	23	6,938,372	0.0069	0.0017

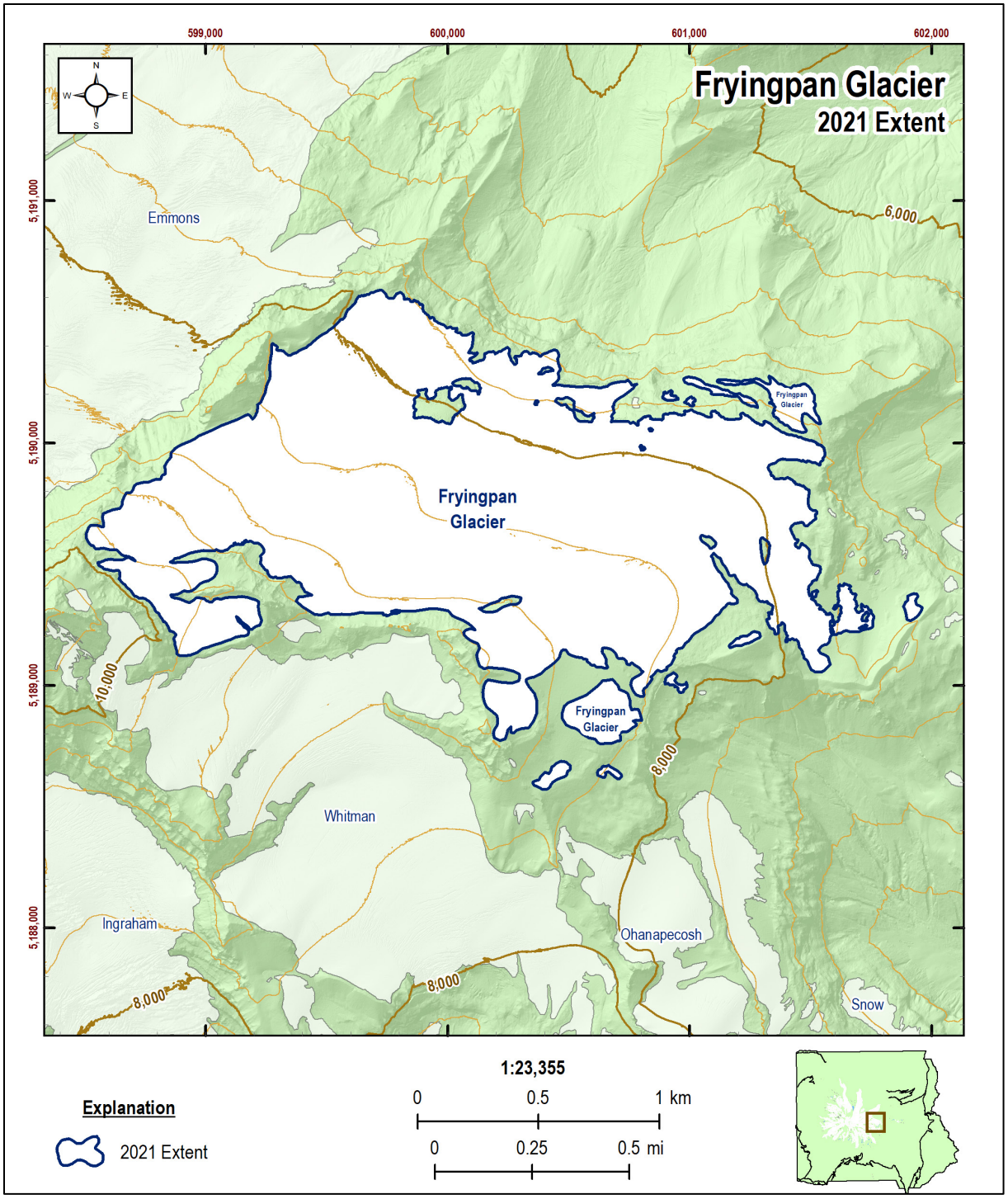


Figure A-7. Year 2021 glacial extent for Fryingpan Glacier.

Table A-7. Year 2021 glacial extent and estimated volume for Fryingpan Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Fryingpan	10	2,993,296	2.993	1.156	11	92,990,091	0.0930	0.0223

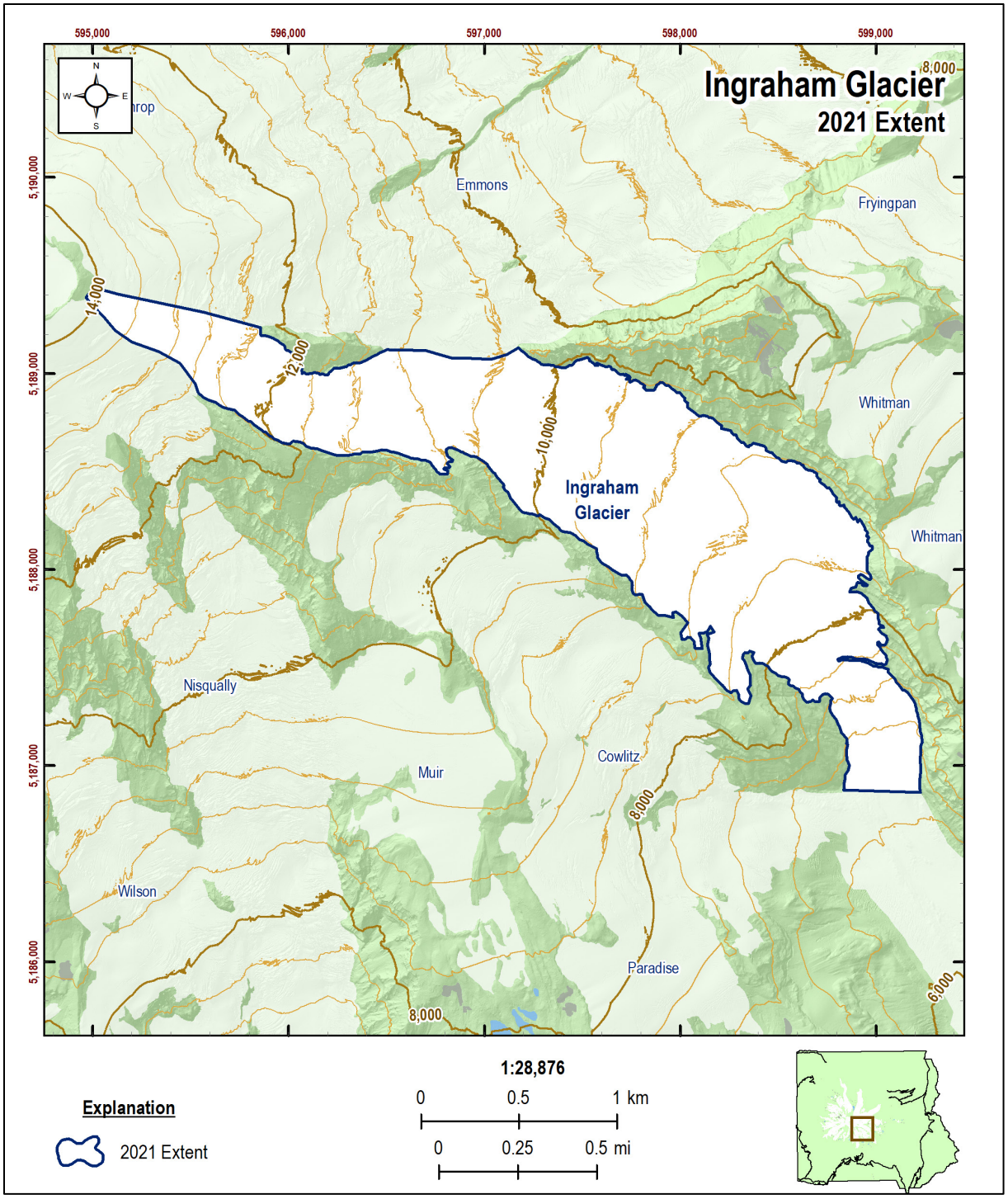


Figure A-8. Year 2021 glacial extent for Ingraham Glacier.

Table A-8. Year 2021 glacial extent and estimated volume for Ingraham Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Ingraham	11	2,962,359	2.962	1.144	10	122,385,999	0.1224	0.0294

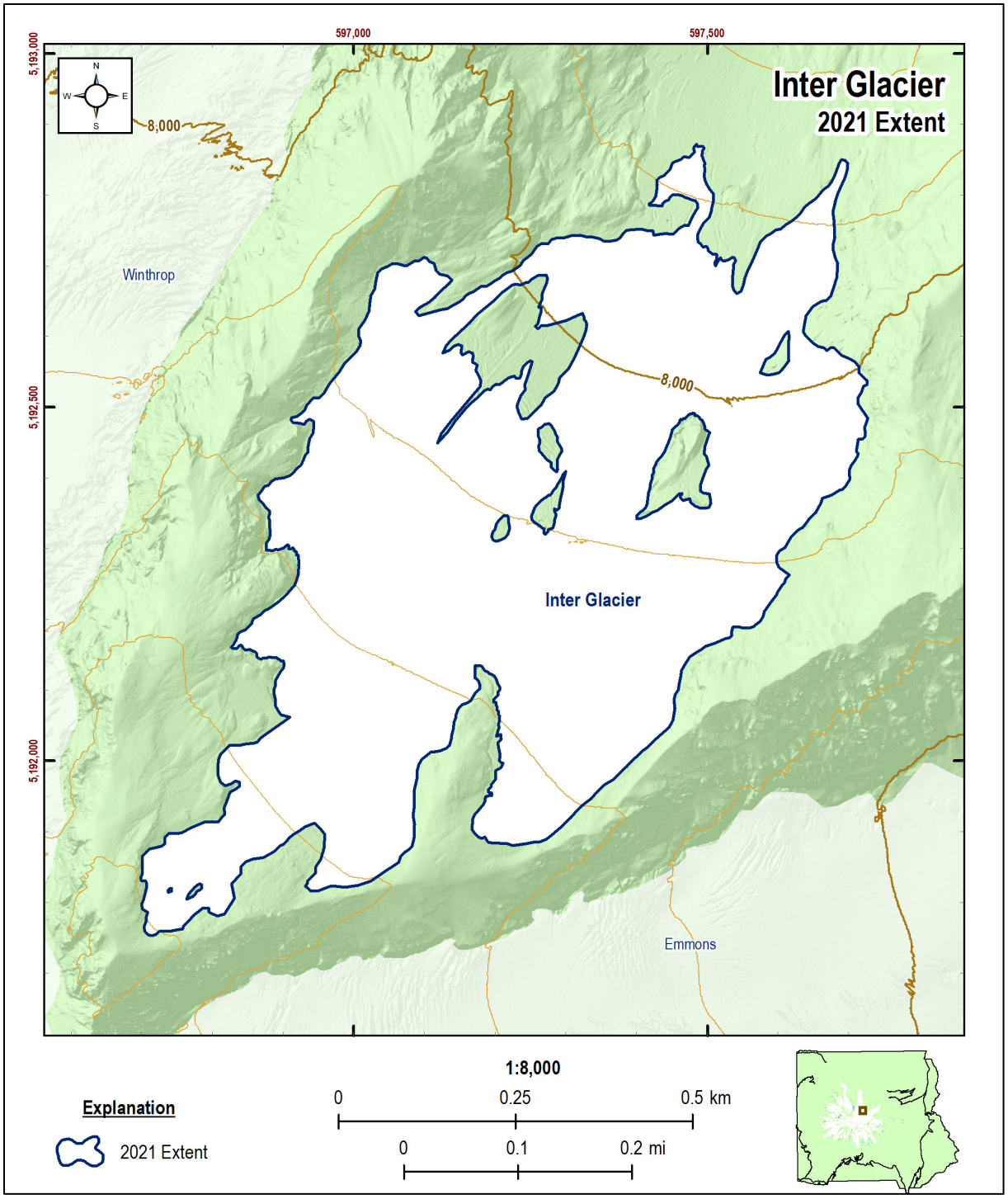


Figure A-9. Year 2021 glacial extent for Inter Glacier.

Table A-.9 Year 2021 glacial extent and estimated volume for Inter Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Inter	22	532,465	0.532	0.206	22	10,433,028	0.0104	0.0025

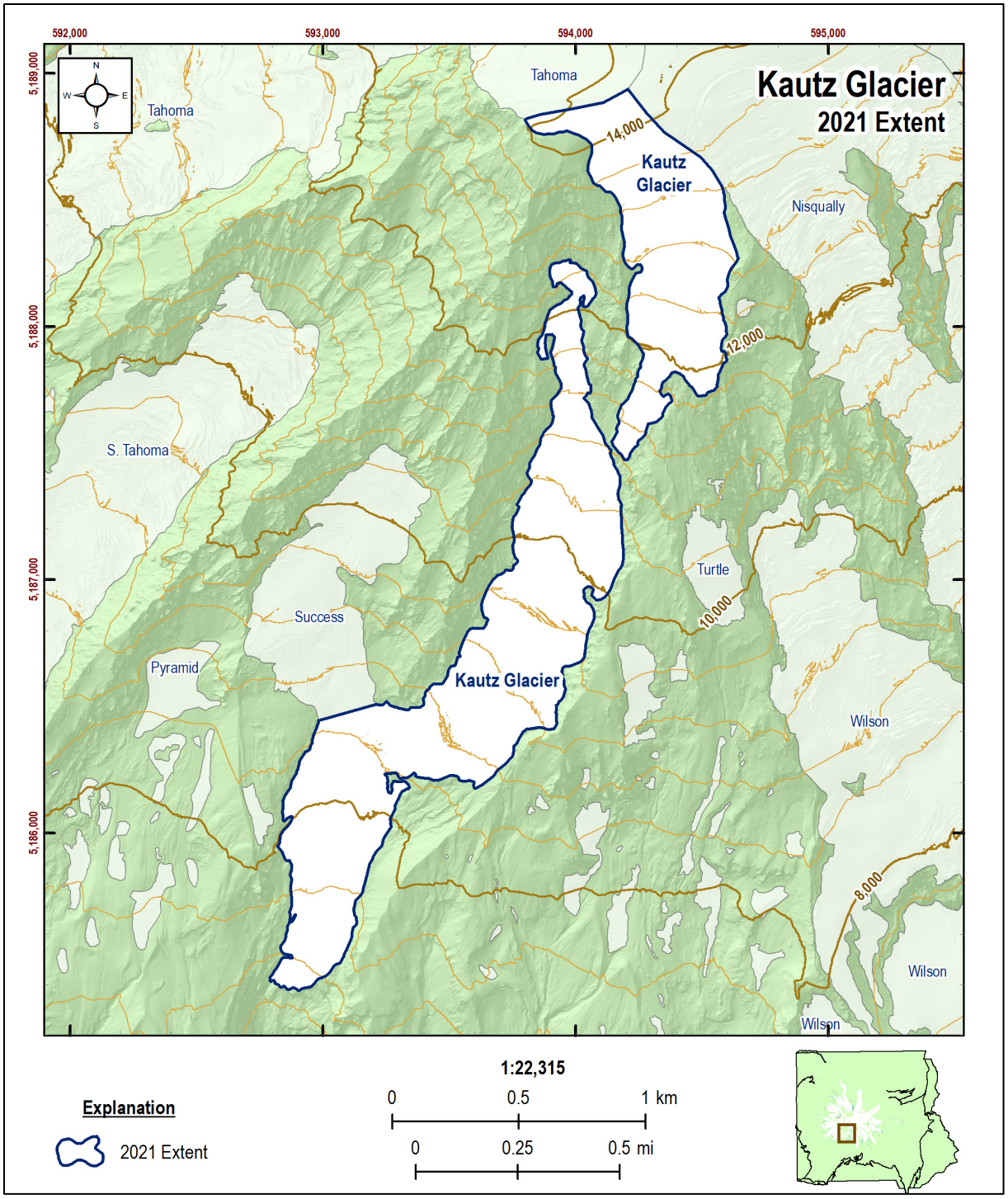


Figure A-10. Year 2021 glacial extent for Kautz Glacier.

Table A-10. Year 2021 glacial extent and estimated volume for Kautz Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Kautz	16	1,560,988	1.561	0.603	16	51,313,169	0.0513	0.0123

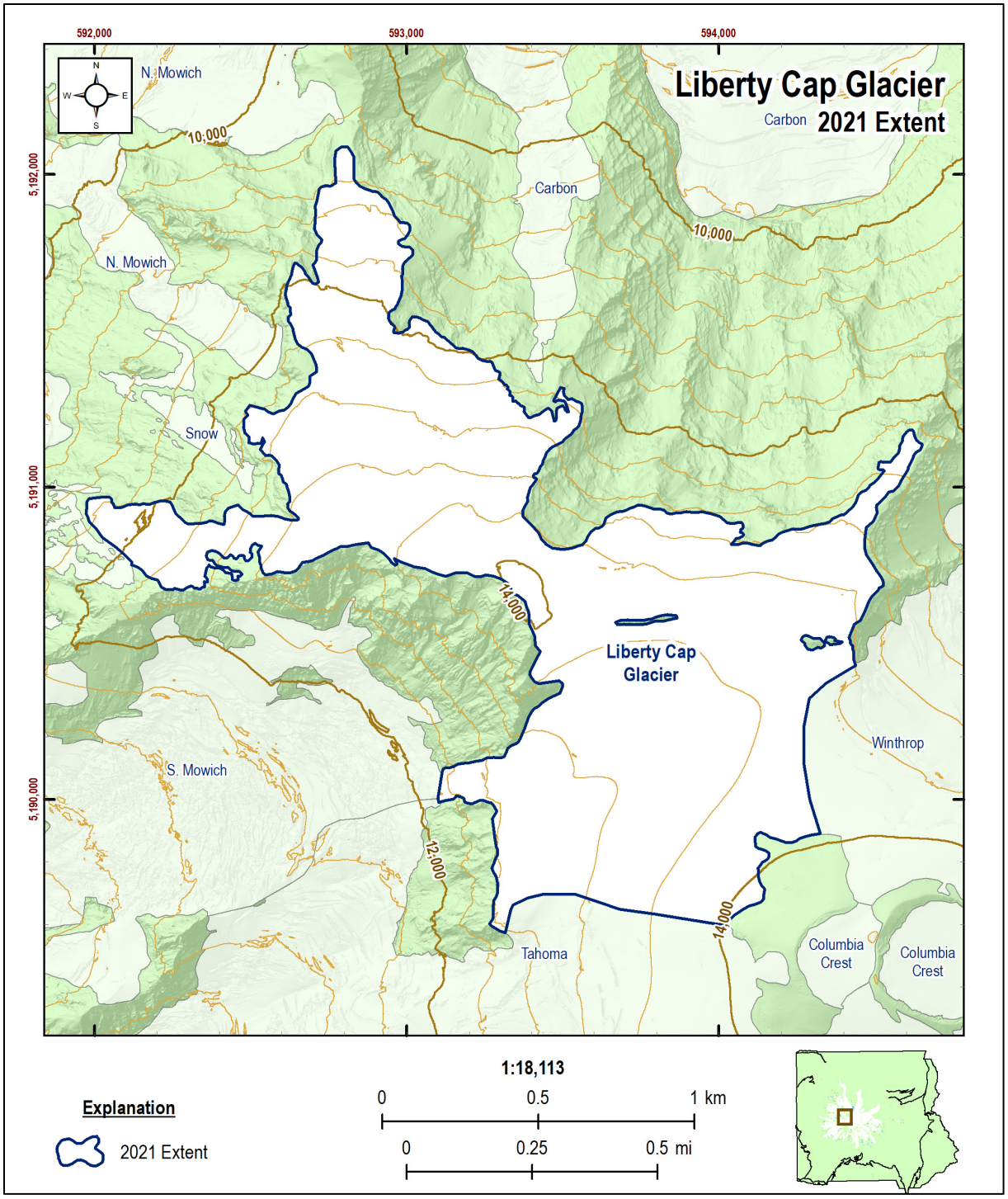


Figure A-11. Year 2021 glacial extent for Liberty Cap Glacier.

Table A-11. Year 2021 glacial extent and estimated volume for Liberty Cap Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Liberty Cap	13	2,075,612	2.076	0.801	12	83,307,324	0.0833	0.0200

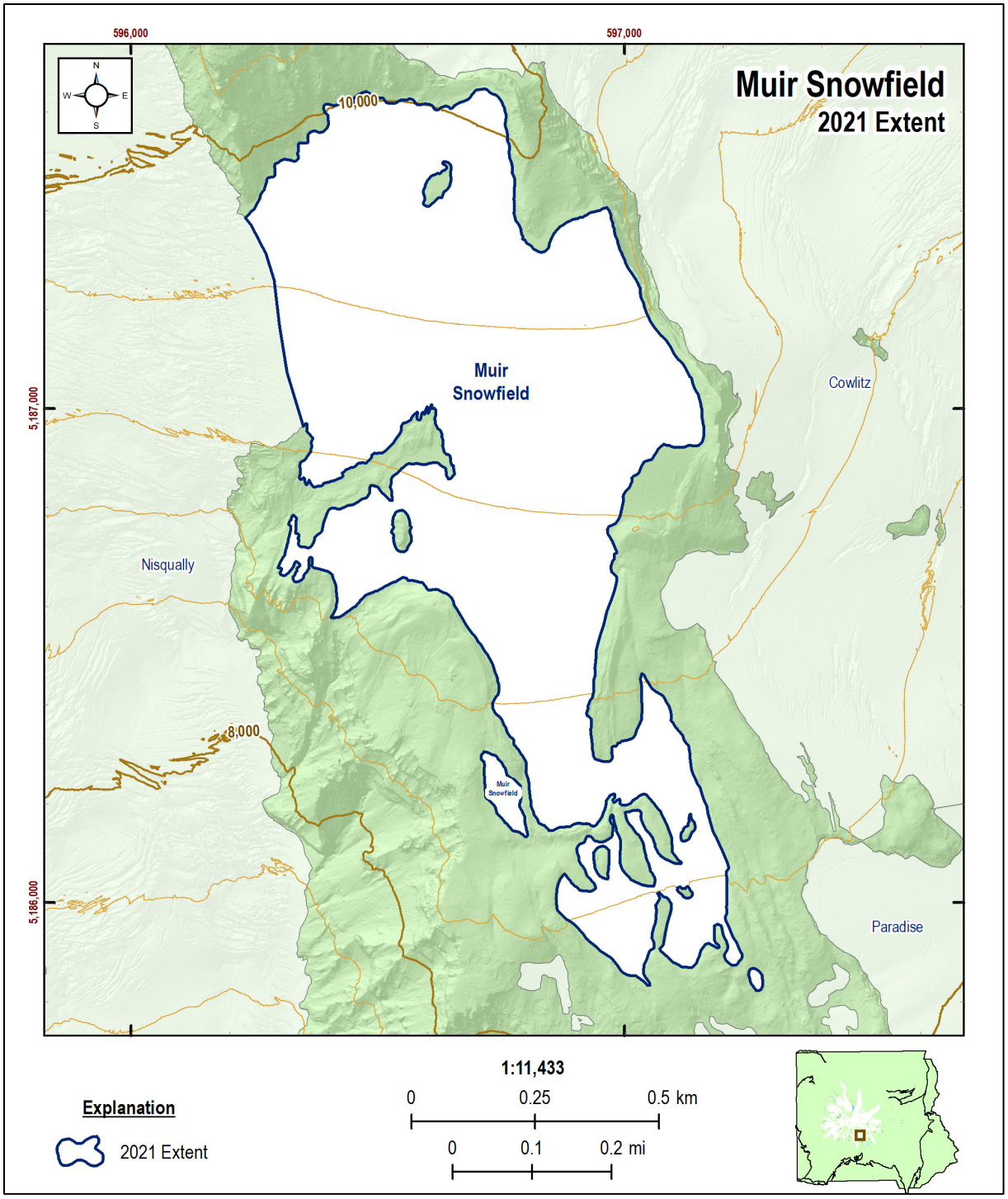


Figure A-12. Year 2021 glacial extent for Muir Snowfield.

Table A-12. Year 2021 glacial extent and estimated volume for Muir Snowfield.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Muir	19	822,523	0.823	0.318	19	18,043,925	0.0180	0.0043

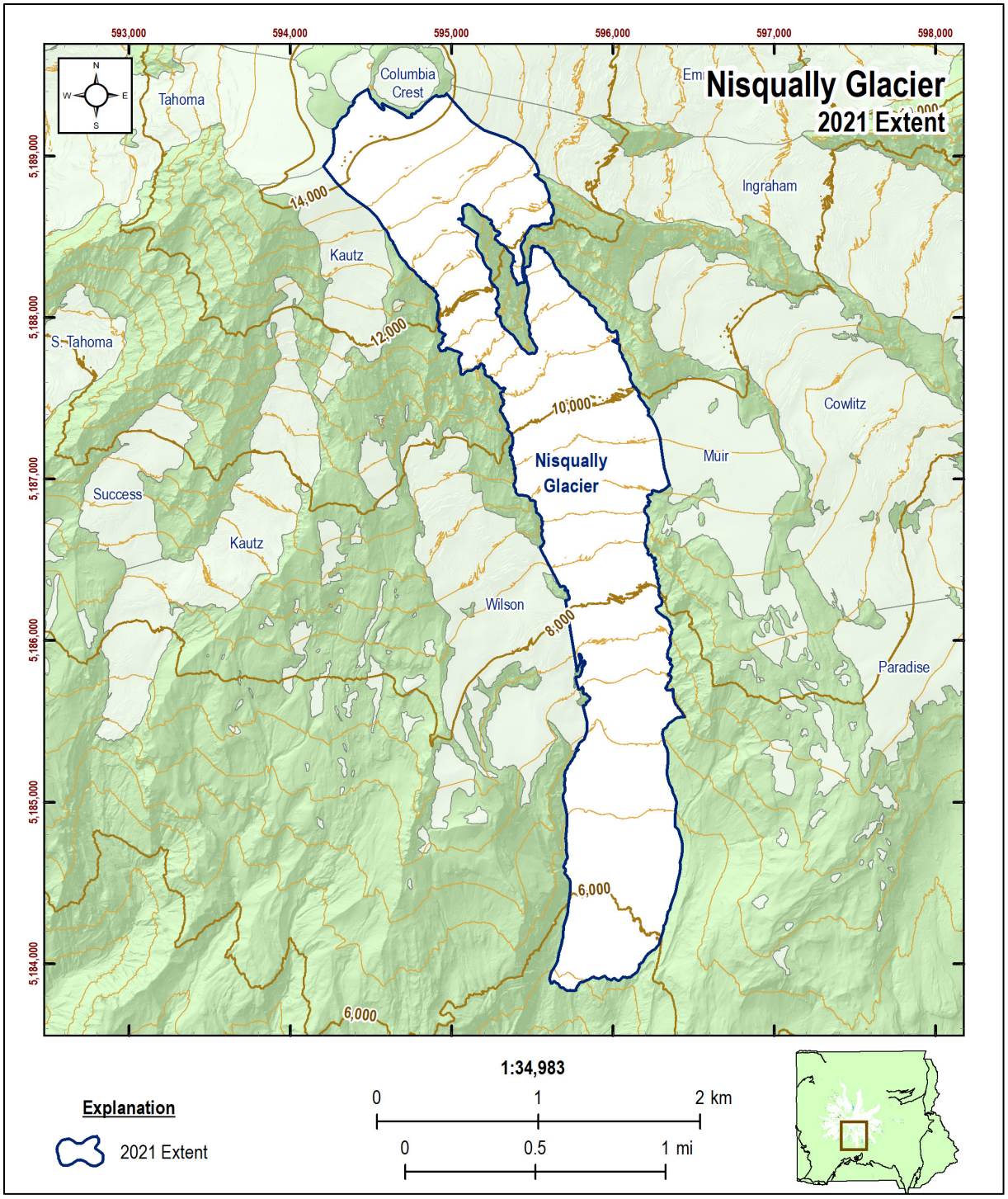


Figure A-13. Year 2021 glacial extent for Nisqually Glacier.

Table A-13. Year 2021 glacial extent and estimated volume for Nisqually Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Nisqually	6	4,102,234	4.102	1.584	6	180,799,587	0.1808	0.0434

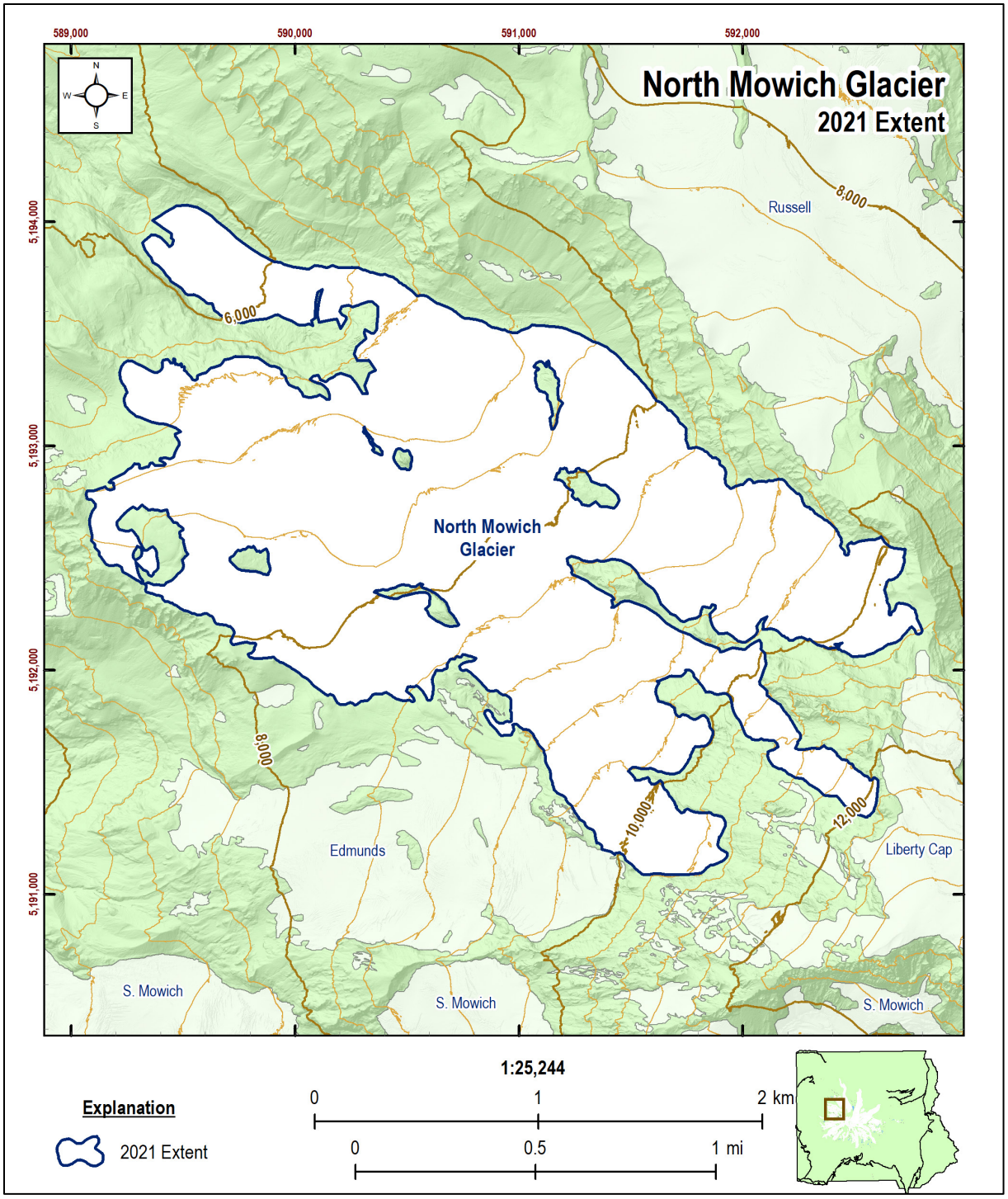


Figure A-14. Year 2021 glacial extent for North Mowich Glacier.

Table A-14. Year 2021 glacial extent and estimated volume for North Mowich Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
North Mowich	5	4,906,908	4.907	1.895	5	209,113,097	0.2091	0.0502

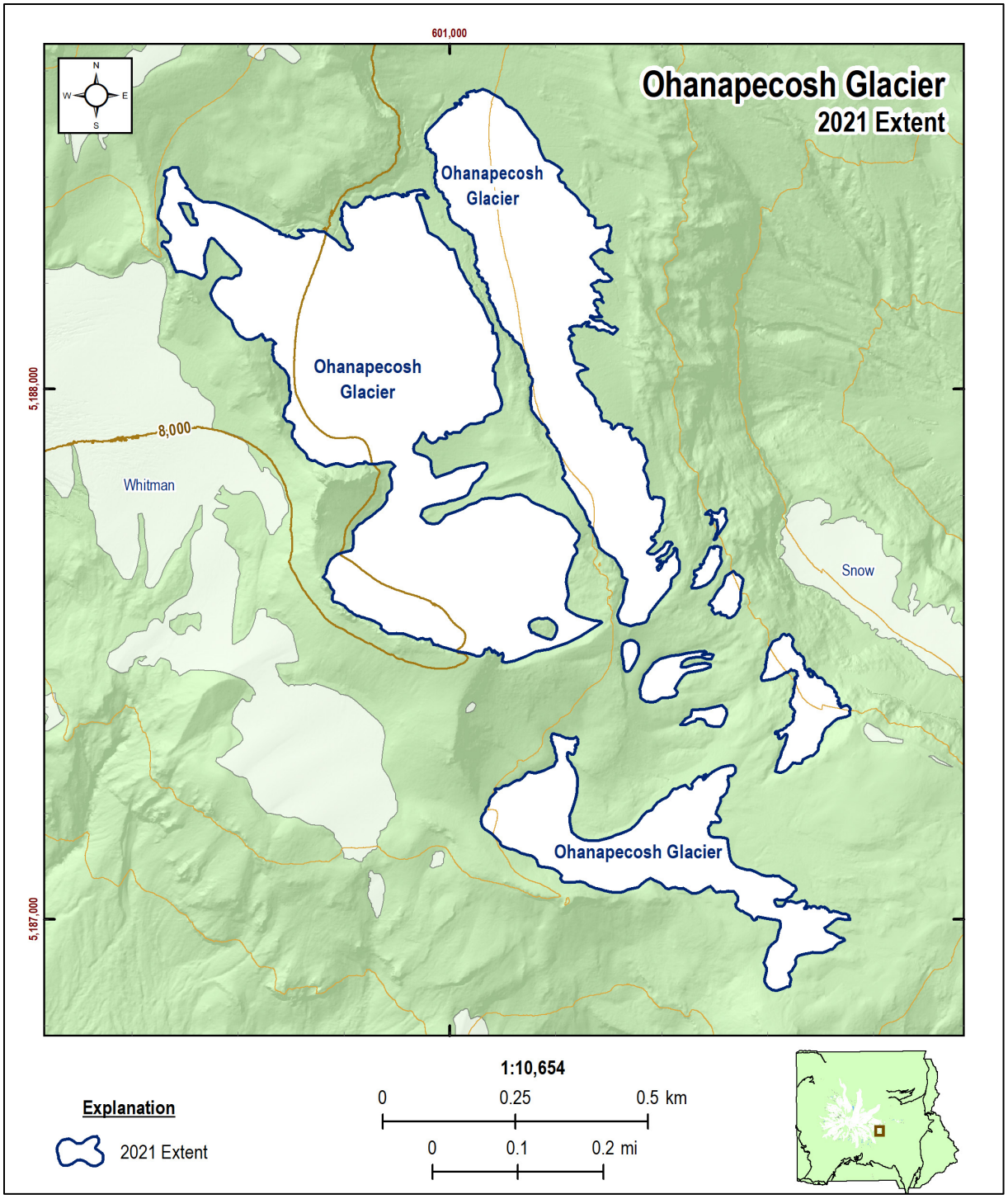


Figure A-15. Year 2021 glacial extent for Ohanapecosh Glacier.

Table A-15. Year 2021 glacial extent and estimated volume for Ohanapecosh Glacier.

Glacier	2021 Glacial Extent				2021 Estimated Glacial Volume			
	Rank	m^2	km^2	mi^2	Rank	m^3	km^3	mi^3
Ohanapecosh	20	615,664	0.616	0.238	20	11,511,976	0.0115	0.0028

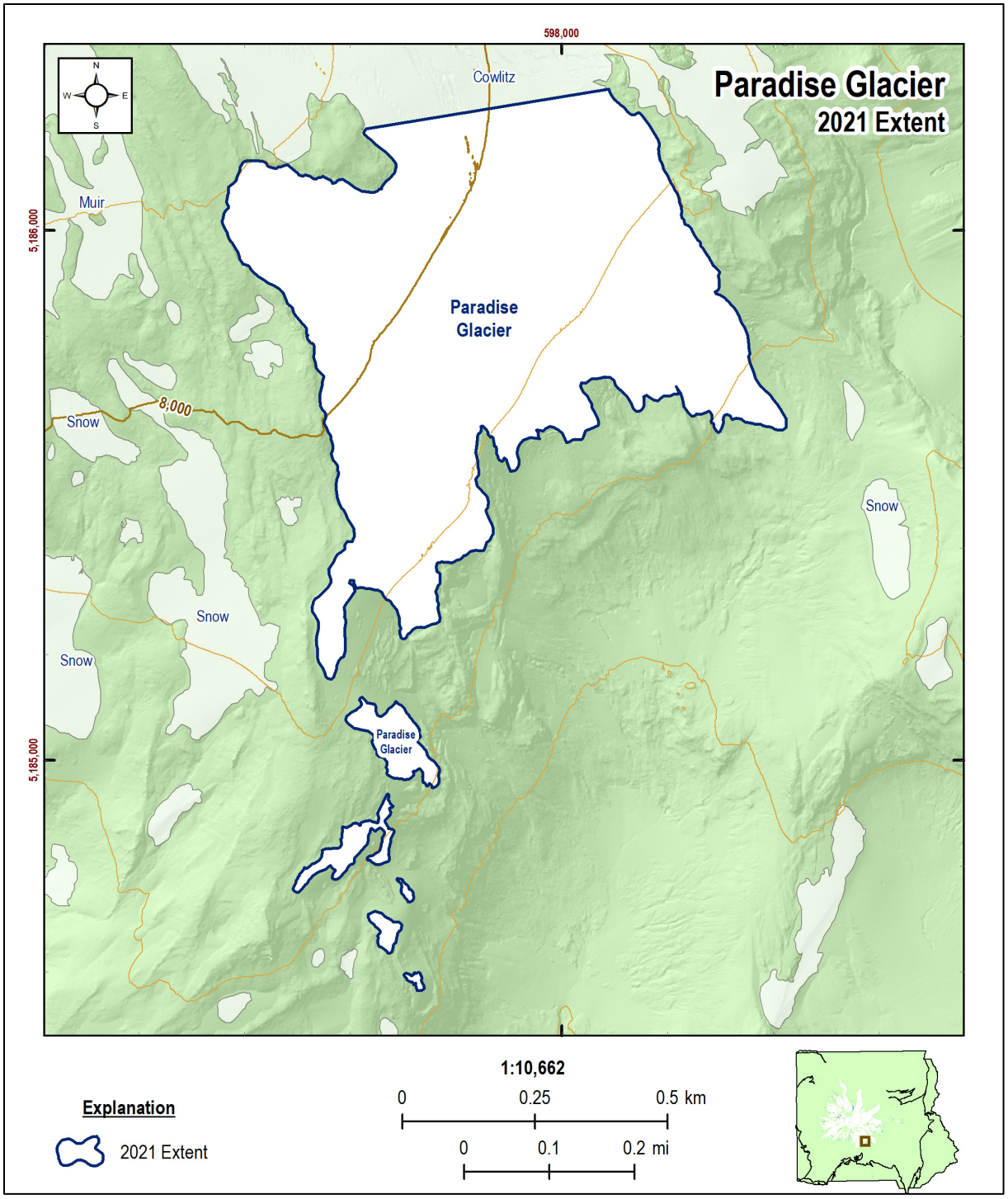


Figure A-16. Year 2021 glacial extent for Paradise Glacier.

Table A-16. Year 2021 glacial extent and estimated volume for Paradise Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Paradise	21	580,582	0.581	0.224	21	11,357,604	0.0114	0.0027

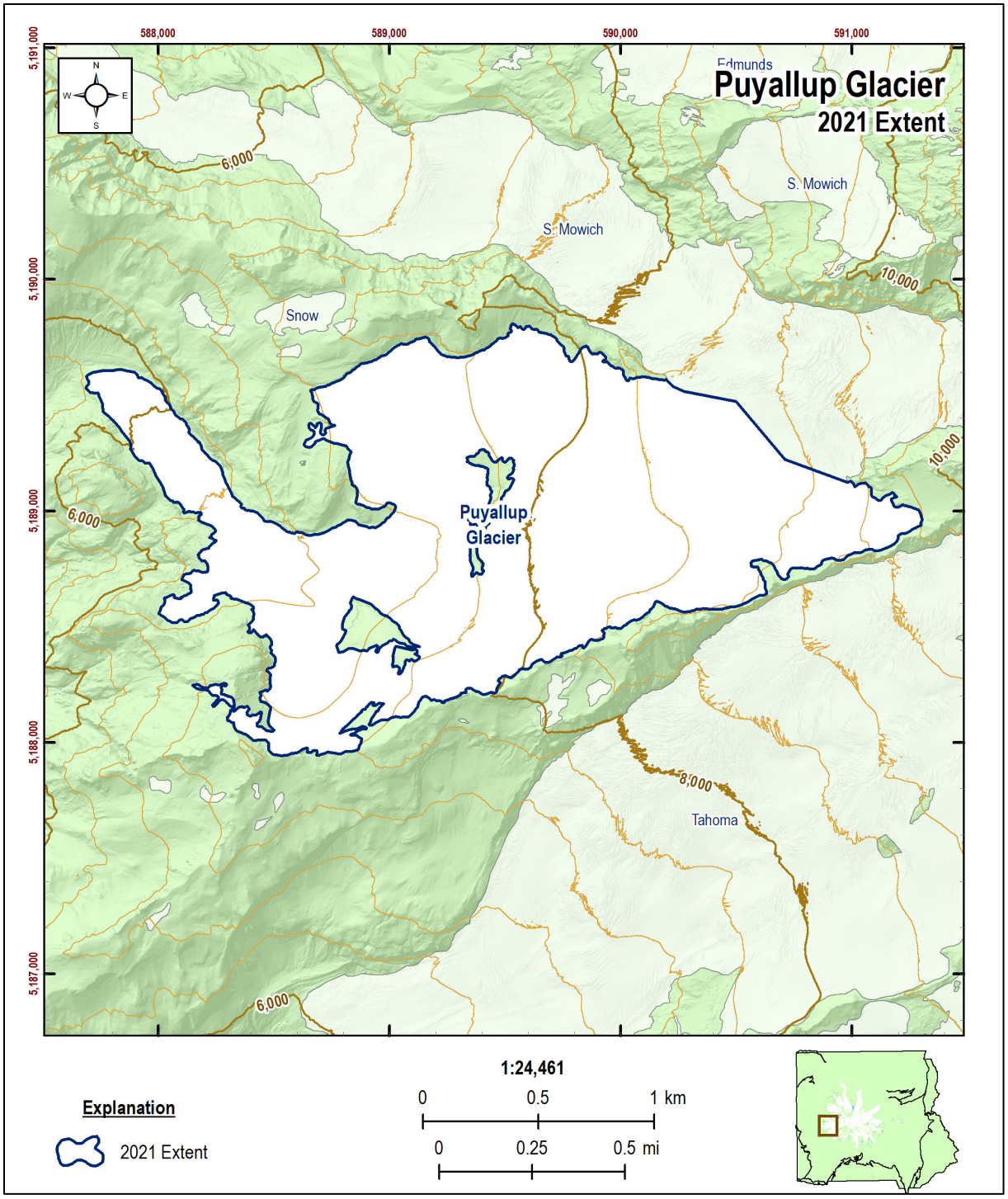


Figure A-17. Year 2021 glacial extent for Puyallup Glacier.

Table A-17. Year 2021 glacial extent and estimated volume for Puyallup Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Puyallup	9	3,097,562	3.098	1.196	9	132,261,921	0.1323	0.0317

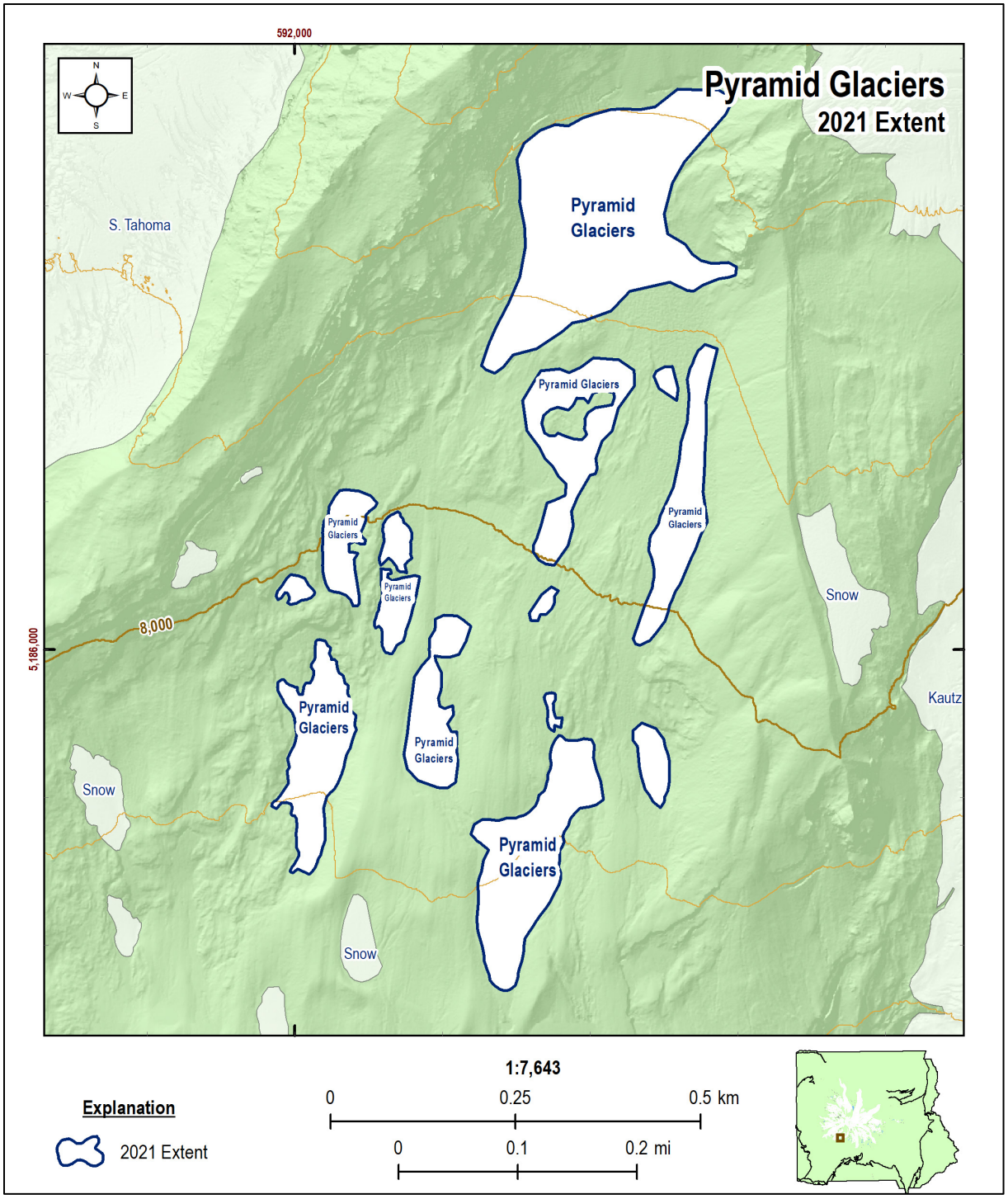


Figure A-18. Year 2021 glacial extent for Pyramid Glaciers.

Table A-18. Year 2021 glacial extent and estimated volume for Pyramid Glaciers.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Pyramid	26	176,038	0.176	0.068	26	2,417,235	0.0024	0.0006

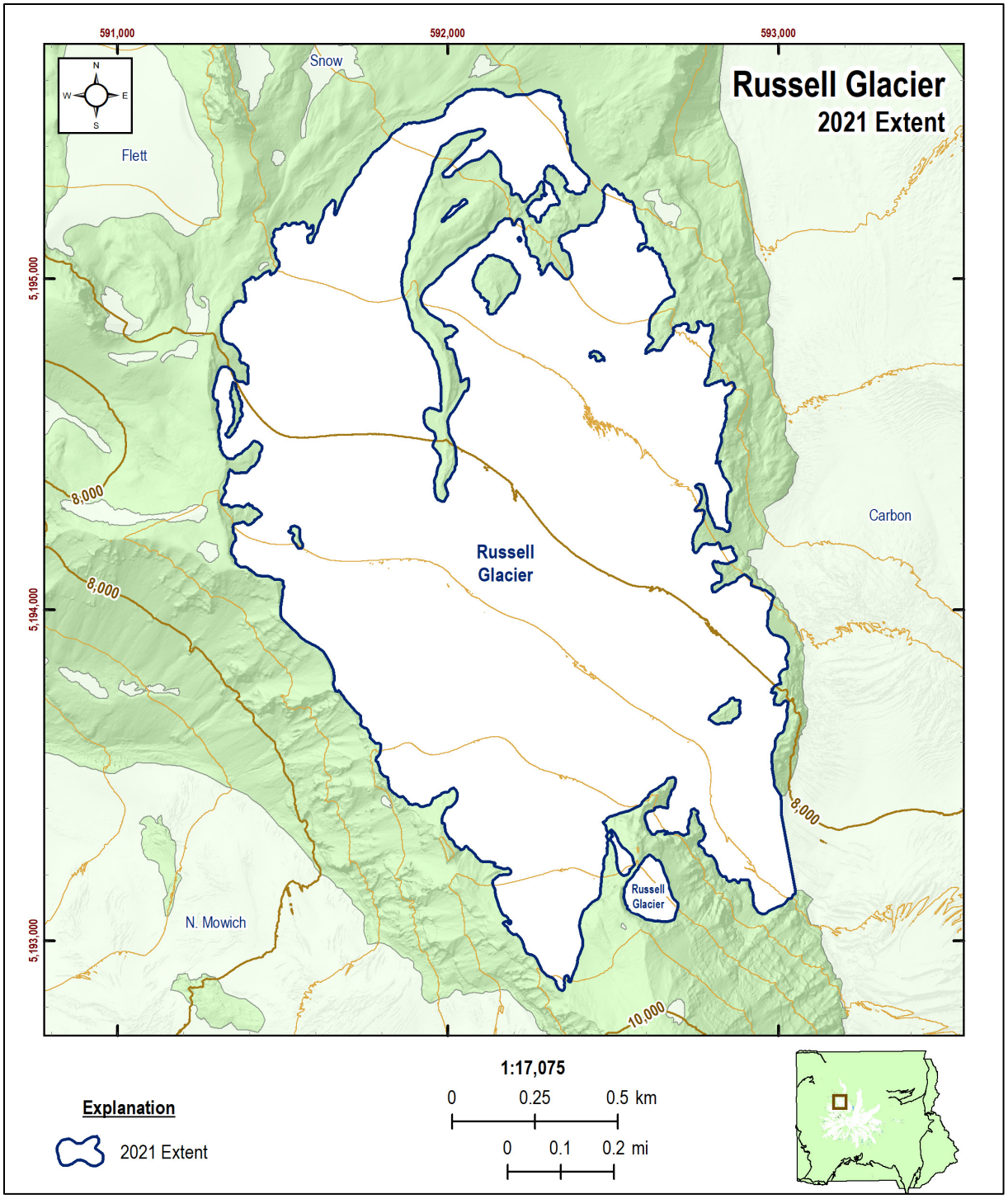


Figure A-19. Year 2021 glacial extent for Russell Glacier.

Table A-19. Year 2021 glacial extent and estimated volume for Russell Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Russell	12	2,705,734	2.706	1.045	13	82,797,338	0.0828	0.0199

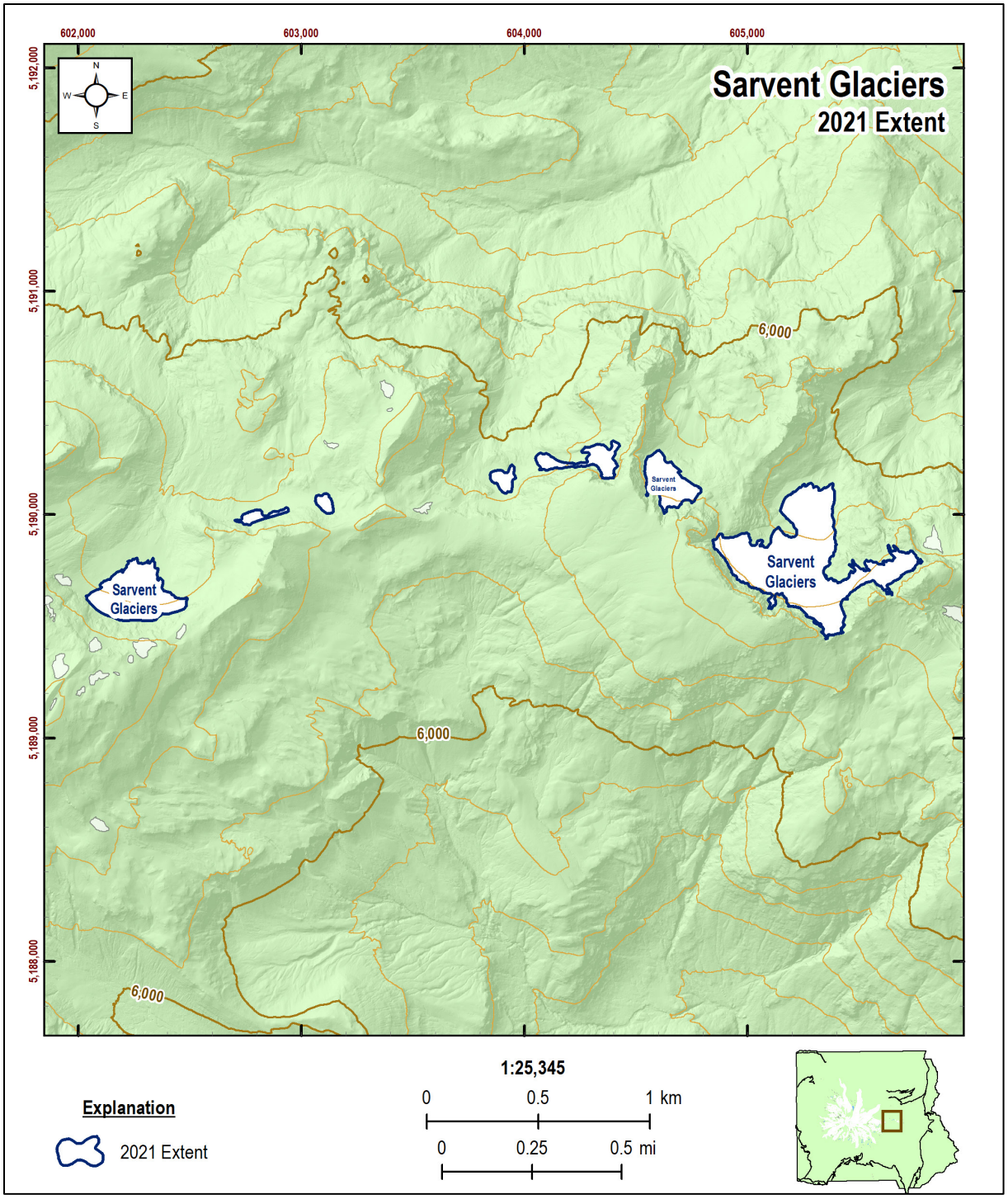


Figure A-20. Year 2021 glacial extent for Sarvent Glaciers.

Table A-20. Year 2021 glacial extent and estimated volume for Sarvent Glaciers.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	Rank	m^2	km^2	mi^2	Rank	m^3	km^3	mi^3
Sarvent	24	380,425	0.380	0.147	25	6,626,725	0.0066	0.0016

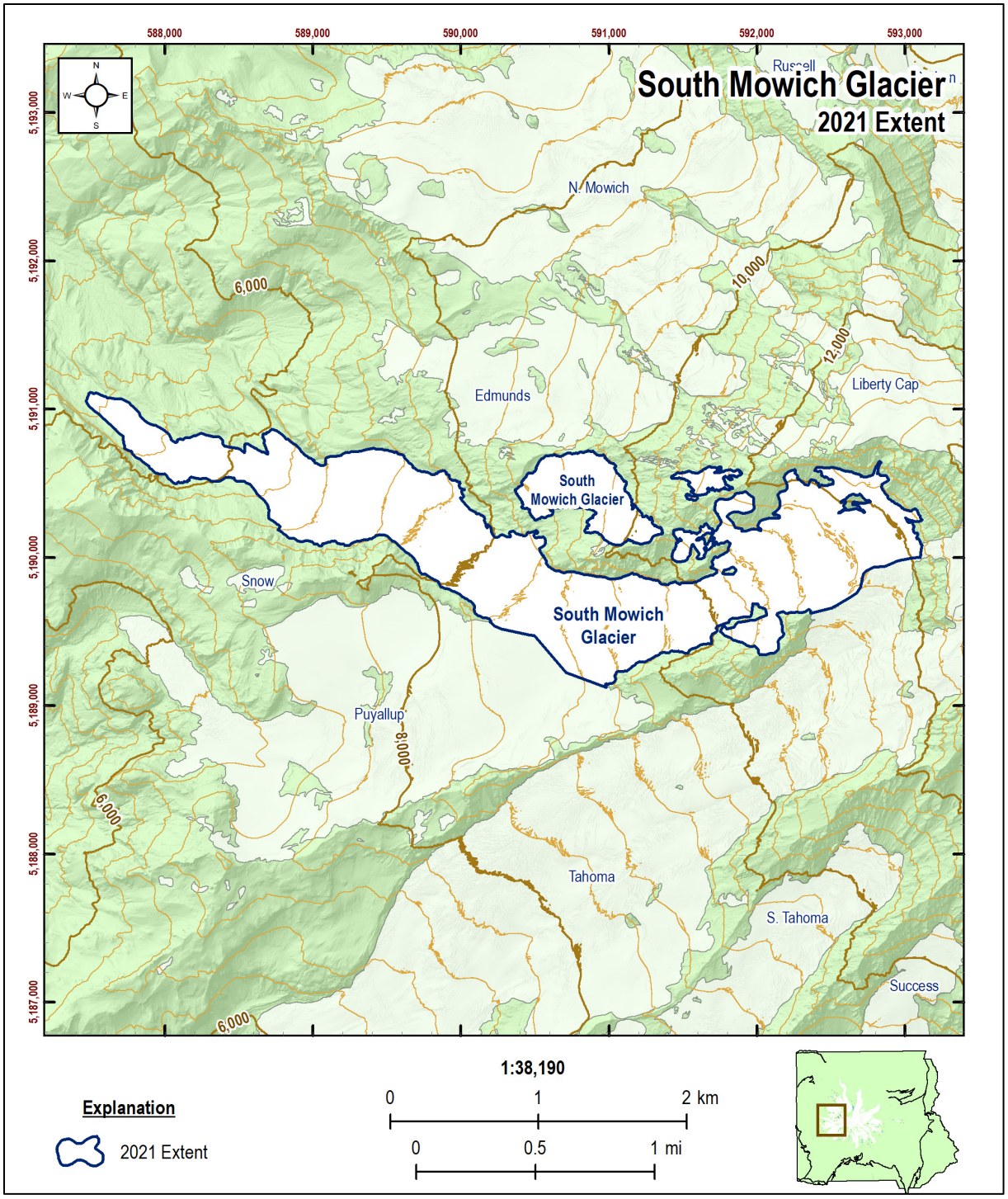


Figure A-21. Year 2021 glacial extent for South Mowich Glacier.

Table A-21. Year 2021 glacial extent and estimated volume for South Mowich Glacier.

Glacier	2021 Glacial Extent				2021 Estimated Glacial Volume			
	Rank	m^2	km^2	mi^2	Rank	m^3	km^3	mi^3
South Mowich	8	3,626,252	3.626	1.400	8	138,675,898	0.1387	0.0333

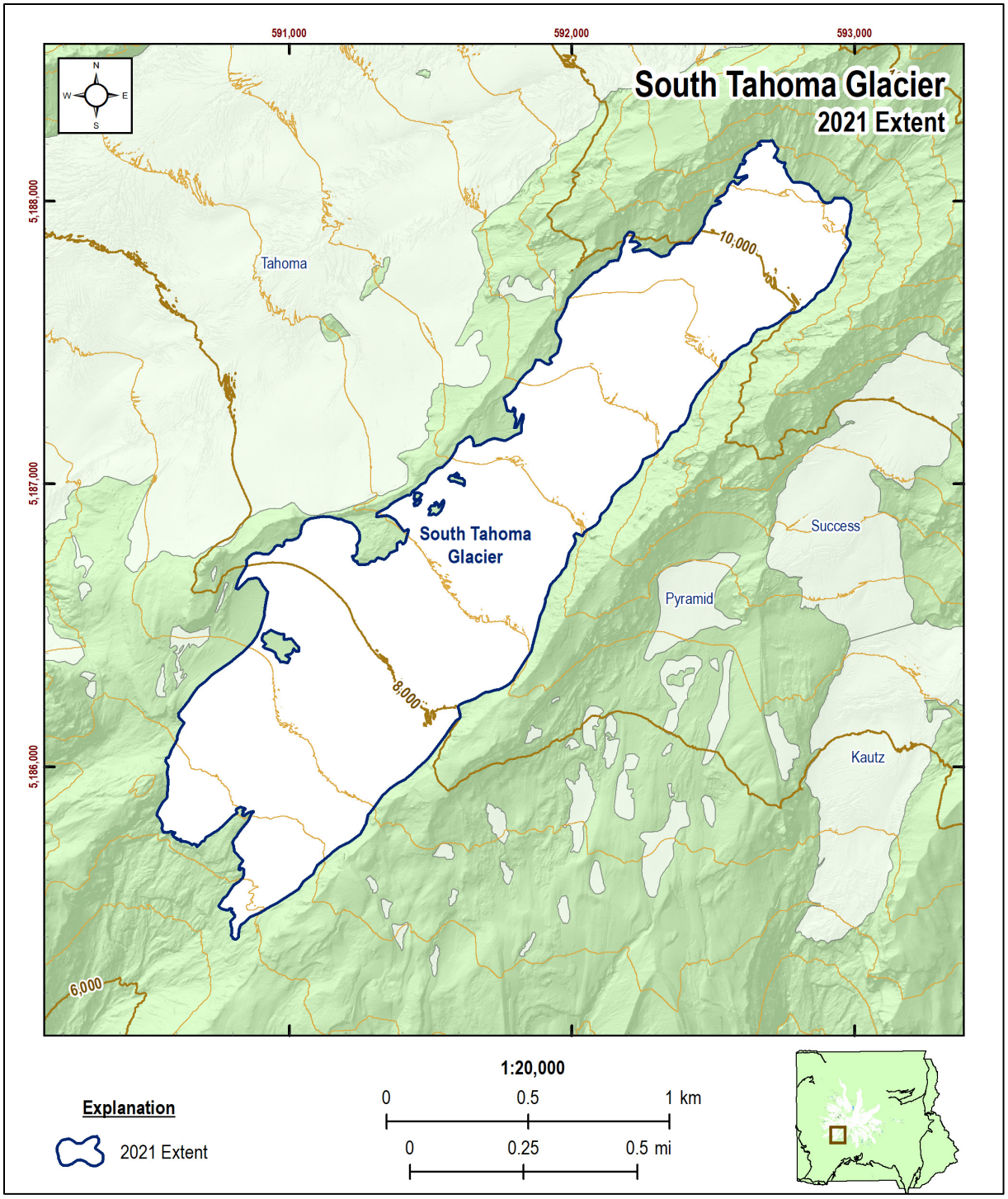


Figure A-22. Year 2021 glacial extent for South Tahoma Glacier.

Table A-22. Year 2021 glacial extent and estimated volume for South Tahoma Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
South Tahoma	14	1,947,002	1.947	0.752	15	70,606,832	0.0706	0.0169

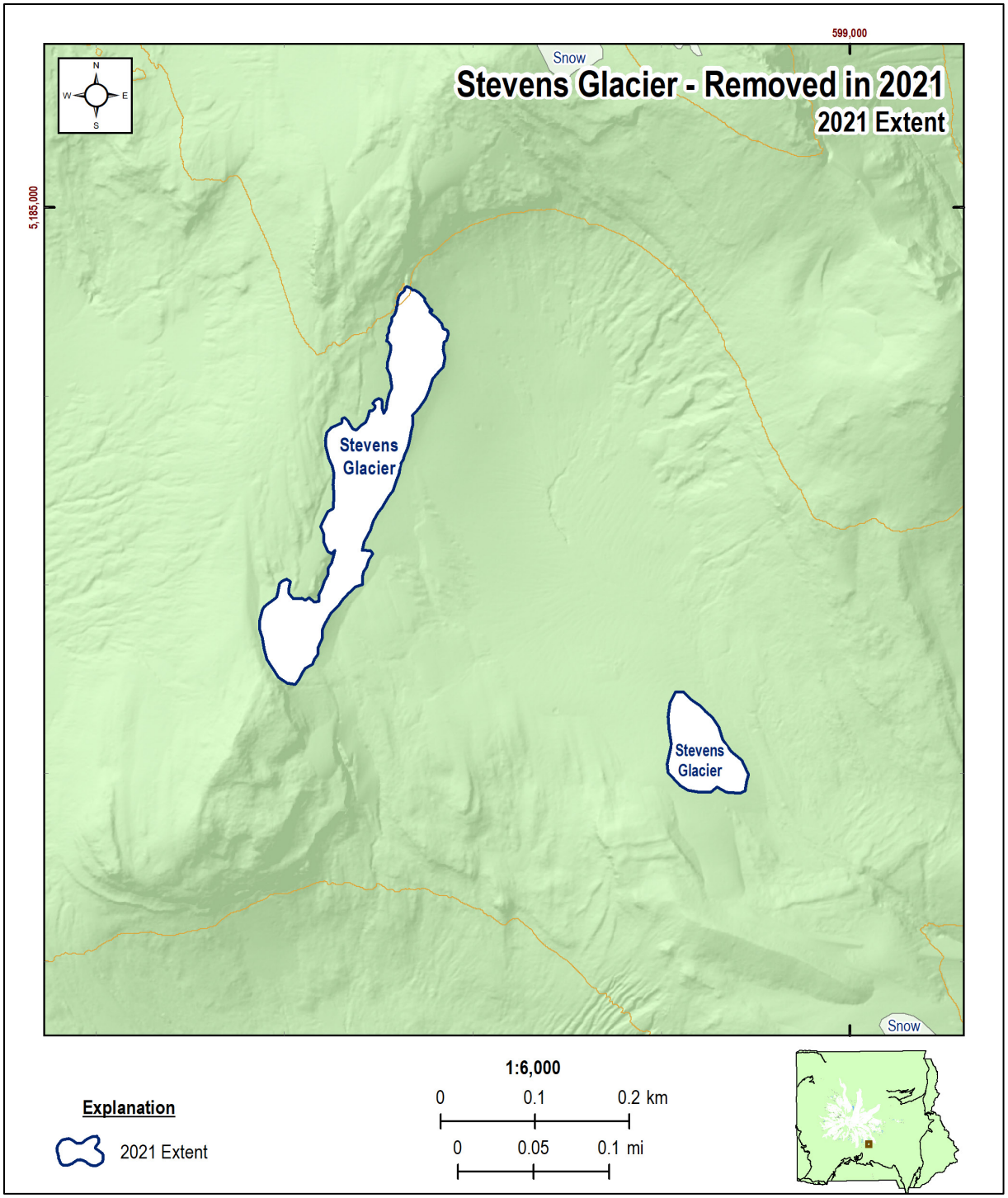


Figure A-23. Year 2021 glacial extent for Stevens Glacier.

Table A-23. Year 2021 glacial extent and estimated volume for Stevens Glacier (no 2021 inventory).

Glacier	2021 Glacial Extent				2021 Estimated Glacial Volume			
	Rank	m^2	km^2	mi^2	Rank	m^3	km^3	mi^3
Stevens	–	–	–	–	–	–	–	–

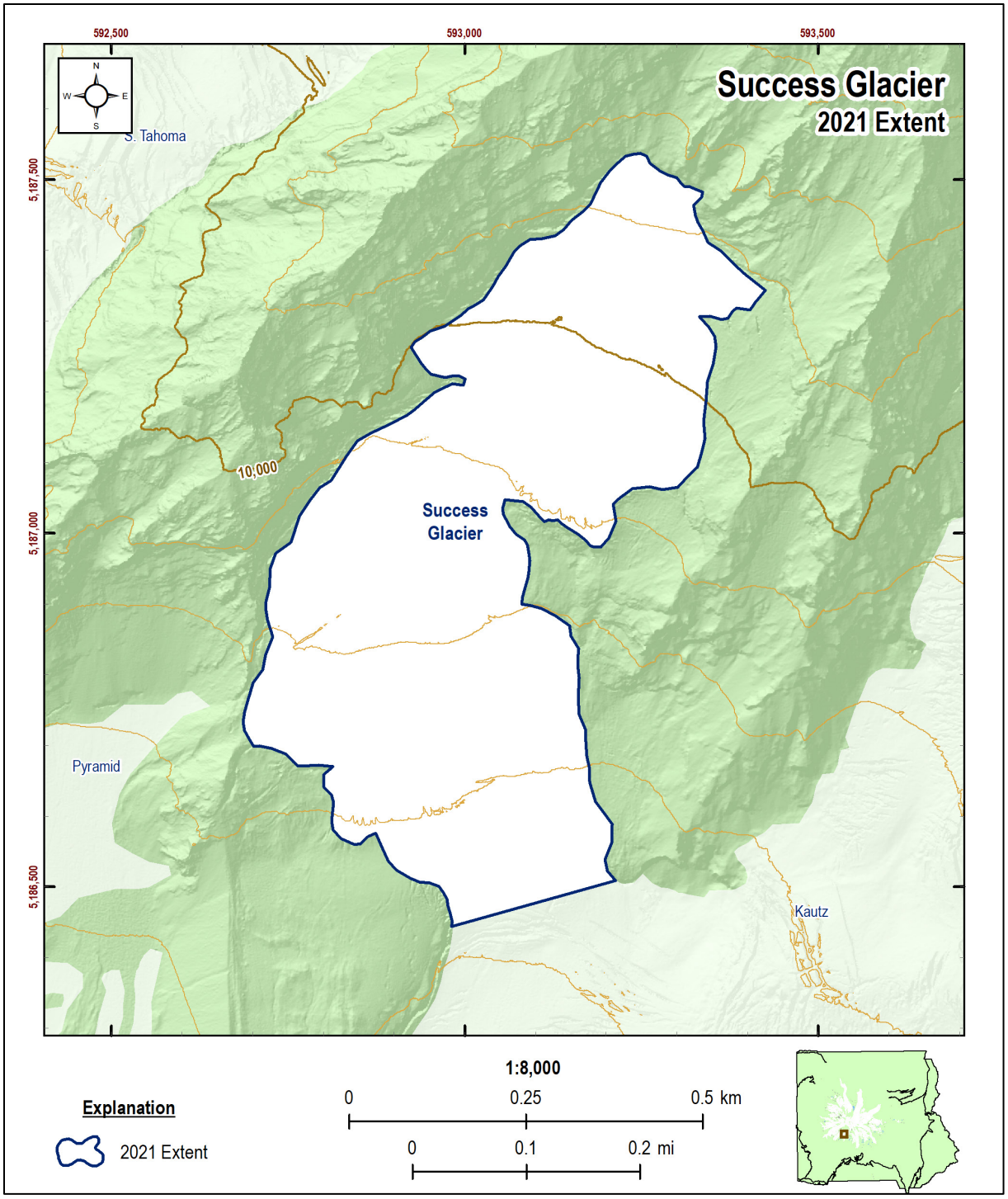


Figure A-24. Year 2021 glacial extent for Success Glacier.

Table A-24. Year 2021 glacial extent and estimated volume for Success Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	Rank	m^2	km^2	mi^2	Rank	m^3	km^3	mi^3
Success	23	396,133	0.396	0.153	24	6,936,194	0.0069	0.0017

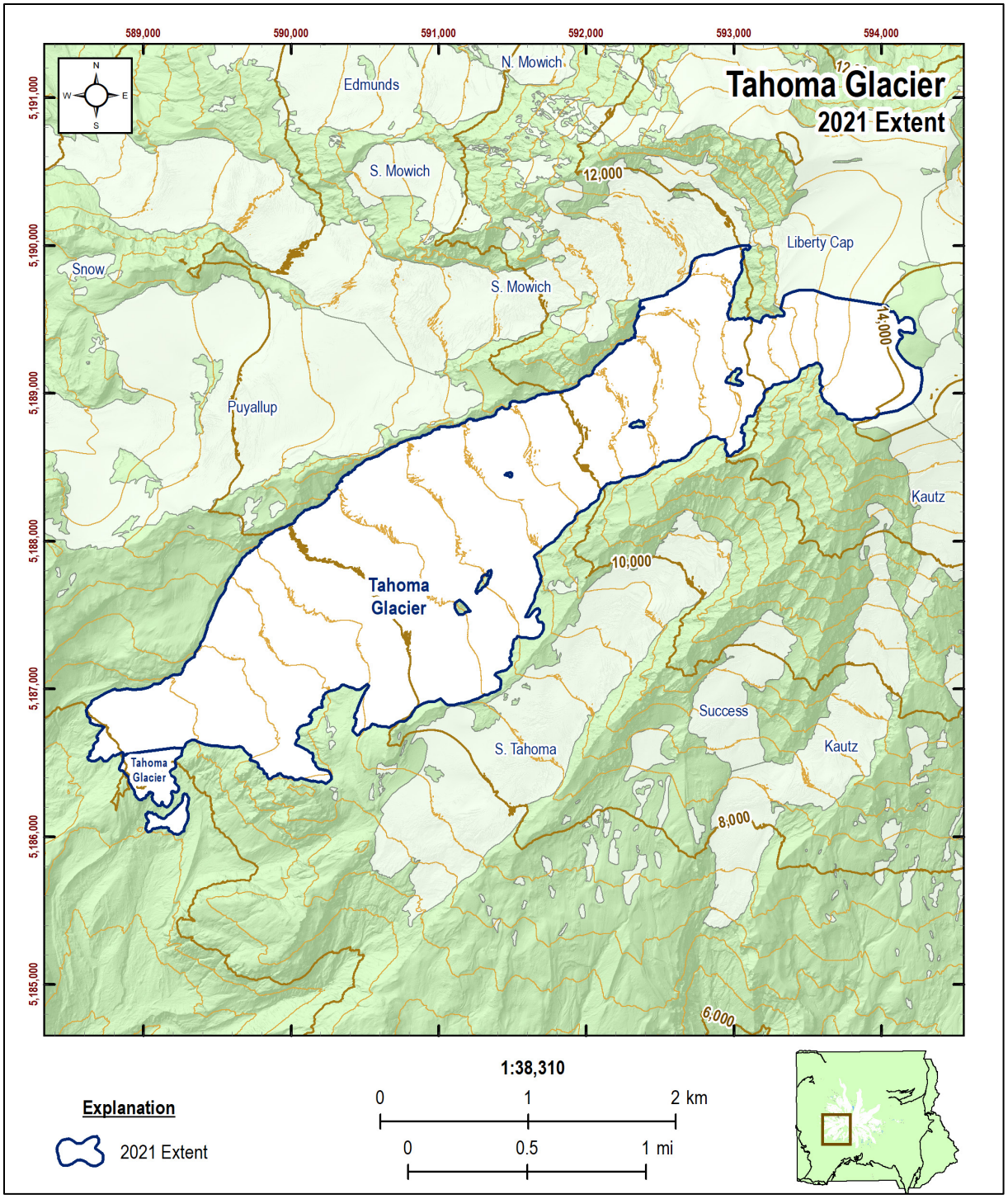


Figure A-25. Year 2021 glacial extent for Tahoma Glacier.

Table A-25. Year 2021 glacial extent and estimated volume for Tahoma Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Tahoma	4	6,432,886	6.433	2.484	4	312,475,088	0.3125	0.0750

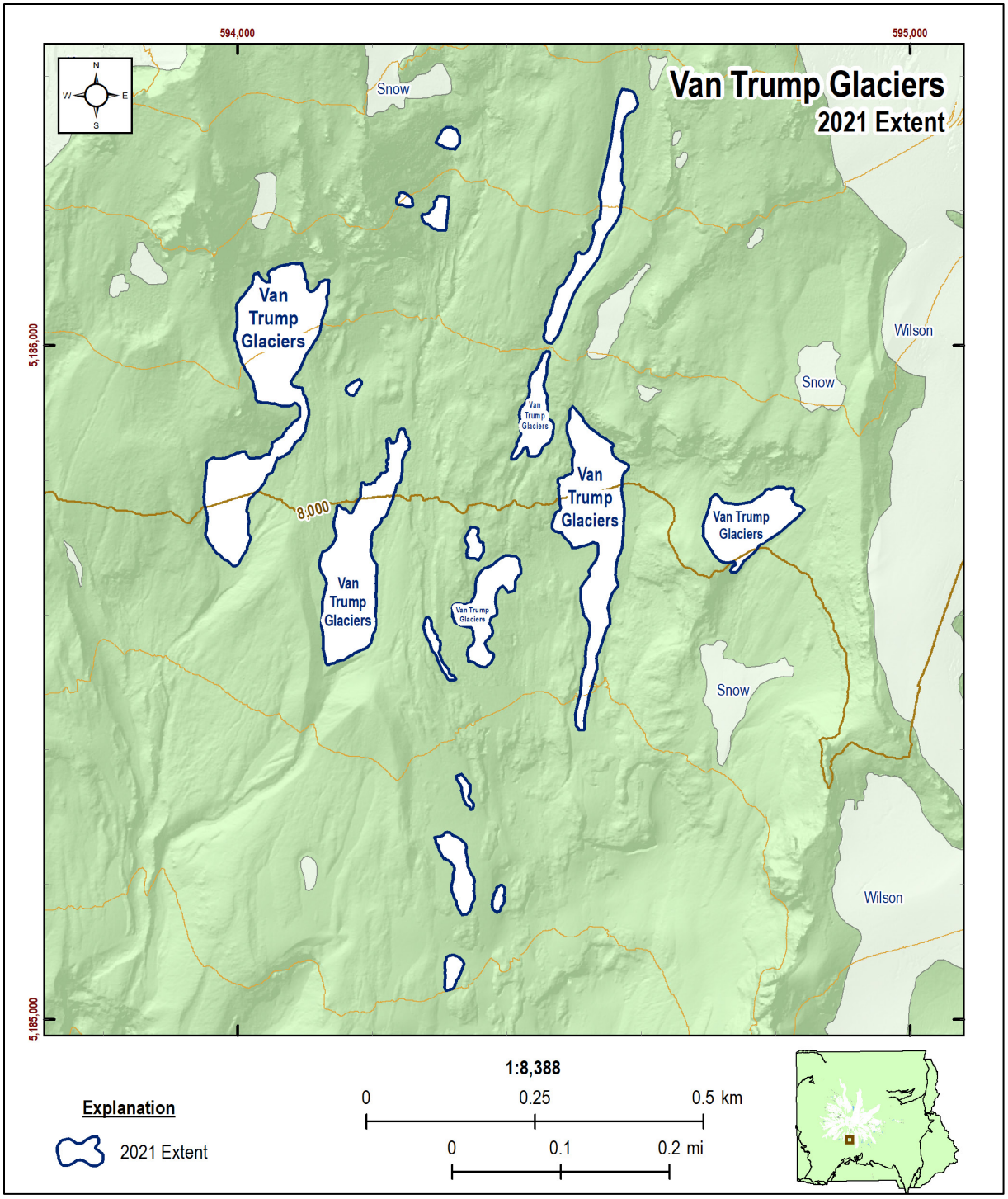


Figure A-26. Year 2021 glacial extent for Van Trump Glaciers.

Table A-26. Year 2021 glacial extent and estimated volume for Van Trump Glaciers.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Van Trump	28	116,854	0.117	0.045	28	1,397,617	0.0014	0.0003

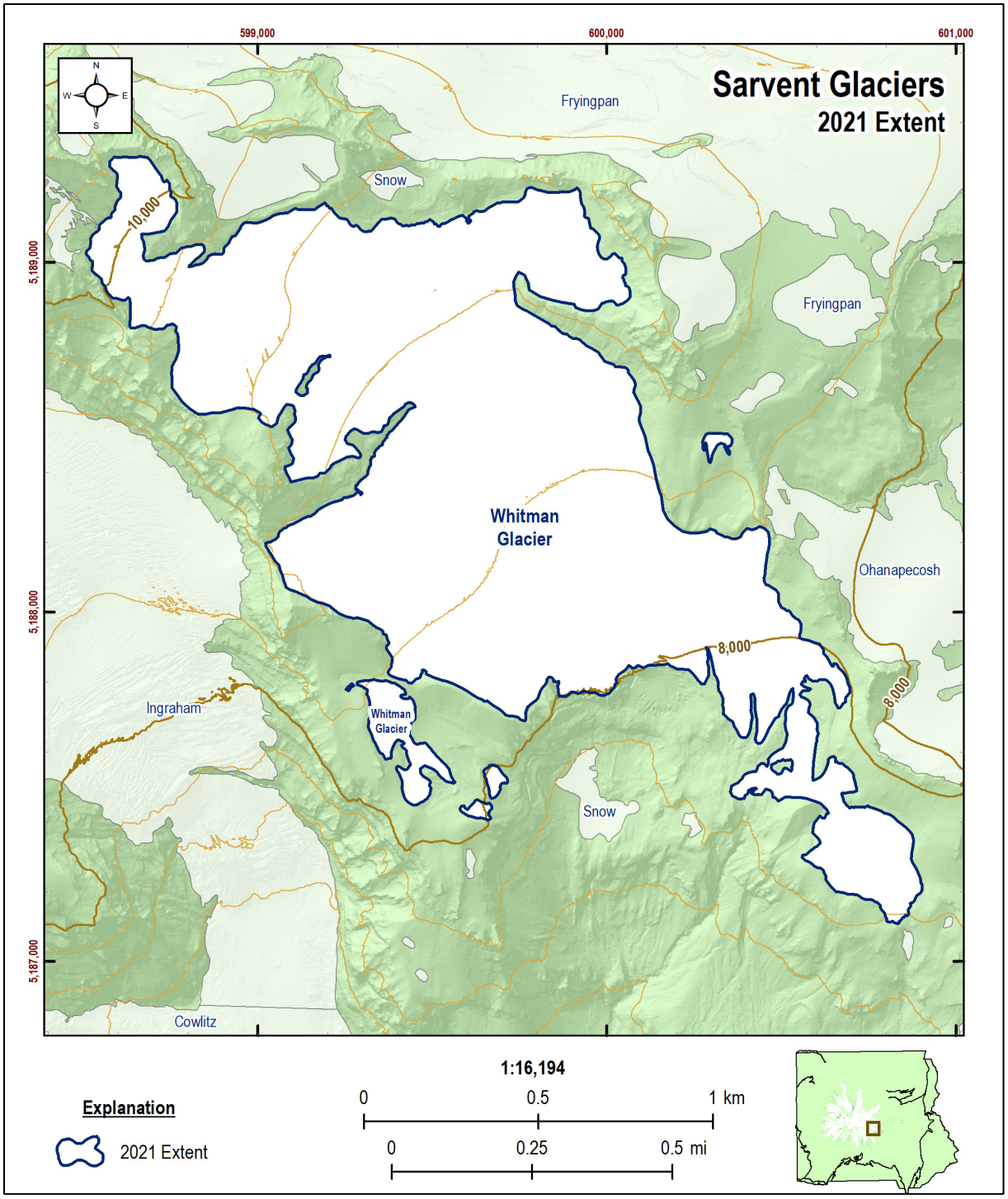


Figure A-27. Year 2021 glacial extent for Whitman Glacier.

Table A-27. Year 2021 glacial extent and estimated volume for Whitman Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Whitman	15	1,845,758	1.846	0.713	14	77,941,924	0.0779	0.0187

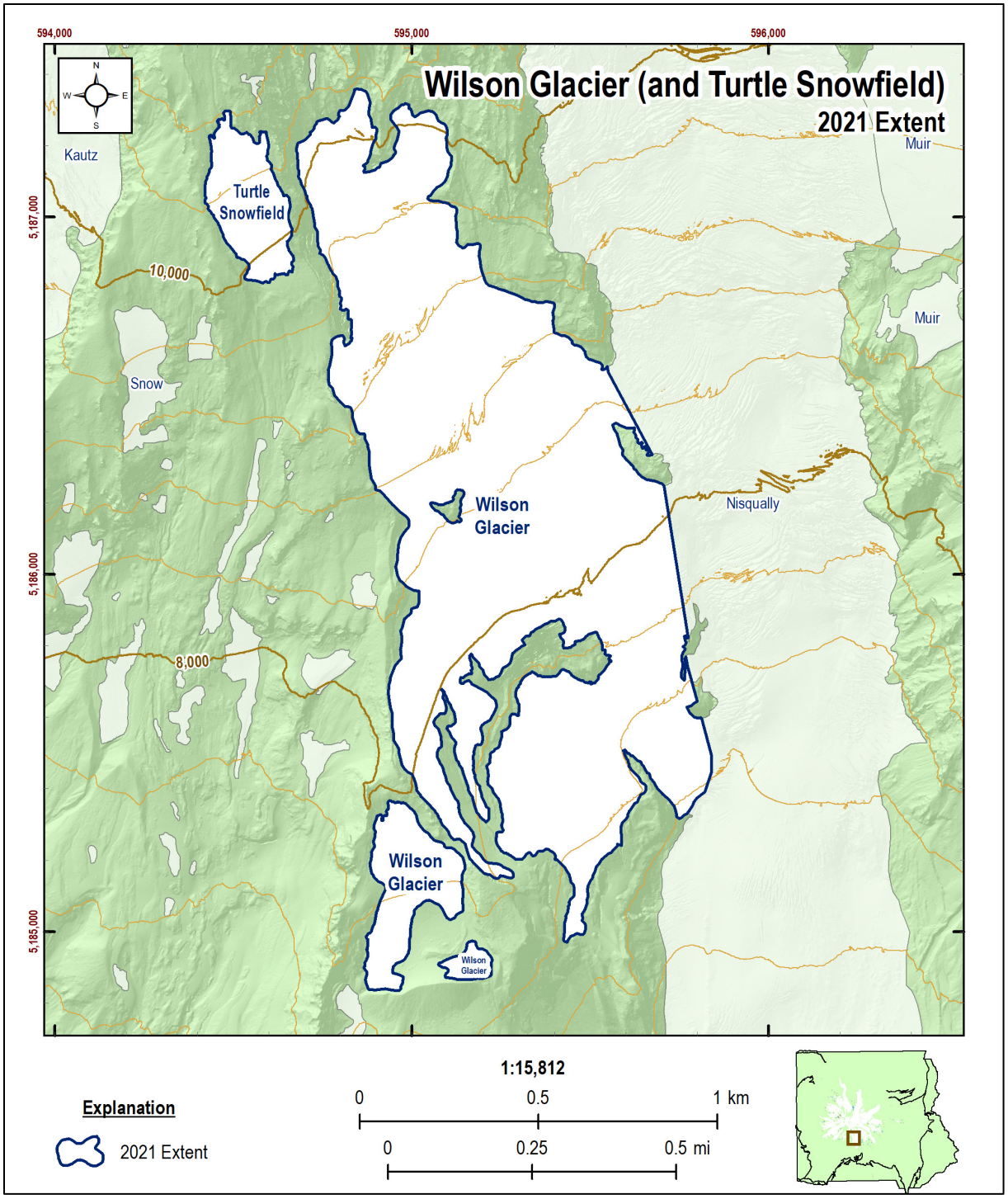


Figure A-28. Year 2021 glacial extent for Wilson Glacier.

Table A-28. Year 2021 glacial extent and estimated volume for Wilson Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Wilson	17	1,459,495	1.459	0.564	17	48,725,420	0.0487	0.0117

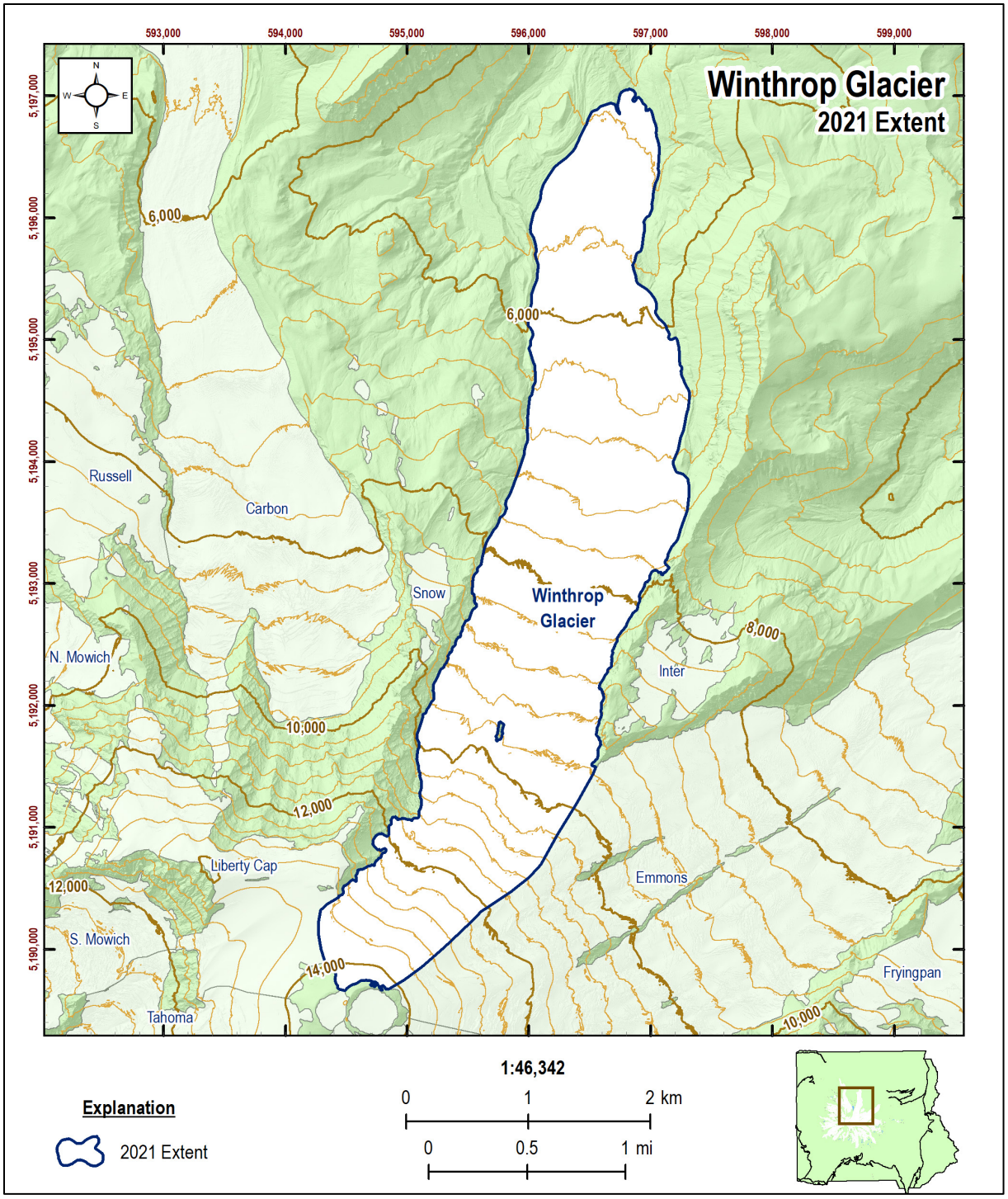


Figure A-29. Year 2021 glacial extent for Winthrop Glacier.

Table A-29. Year 2021 glacial extent and estimated volume for Winthrop Glacier.

	2021 Glacial Extent				2021 Estimated Glacial Volume			
Glacier	**Rank**	**m^2**	**km^2**	**mi^2**	**Rank**	**m^3**	**km^3**	**mi^3**
Winthrop	2	8,687,940	8.688	3.354	3	486,489,224	0.4865	0.1167

Appendix B: Detail Maps of Individual Named Glaciers with Change Over Time at Mount Rainier

Notes for all appendix maps and tables (Figures B-1 through B-25, and Tables B-1 through B-50):

- Map grids are plotted in NAD 1983 UTM Zone 10 North (meters).
- Background hill shade based on 2007/8 LiDAR Survey.
- Current aerial extent of glaciers is from Table 4.
- Volume of glaciers is from Table 15.
- Change in extent of glaciers is from Table 7.
- Values in the comparison grid at the bottom of each page are change in extent in square kilometers and percent change in extent over the respective periods.
- The 1896 glacier map did not include separate features for the Flett, Ohanapecosh, or Sarvent Glaciers. As such, the comparison tables show "---" for the 1896 features.

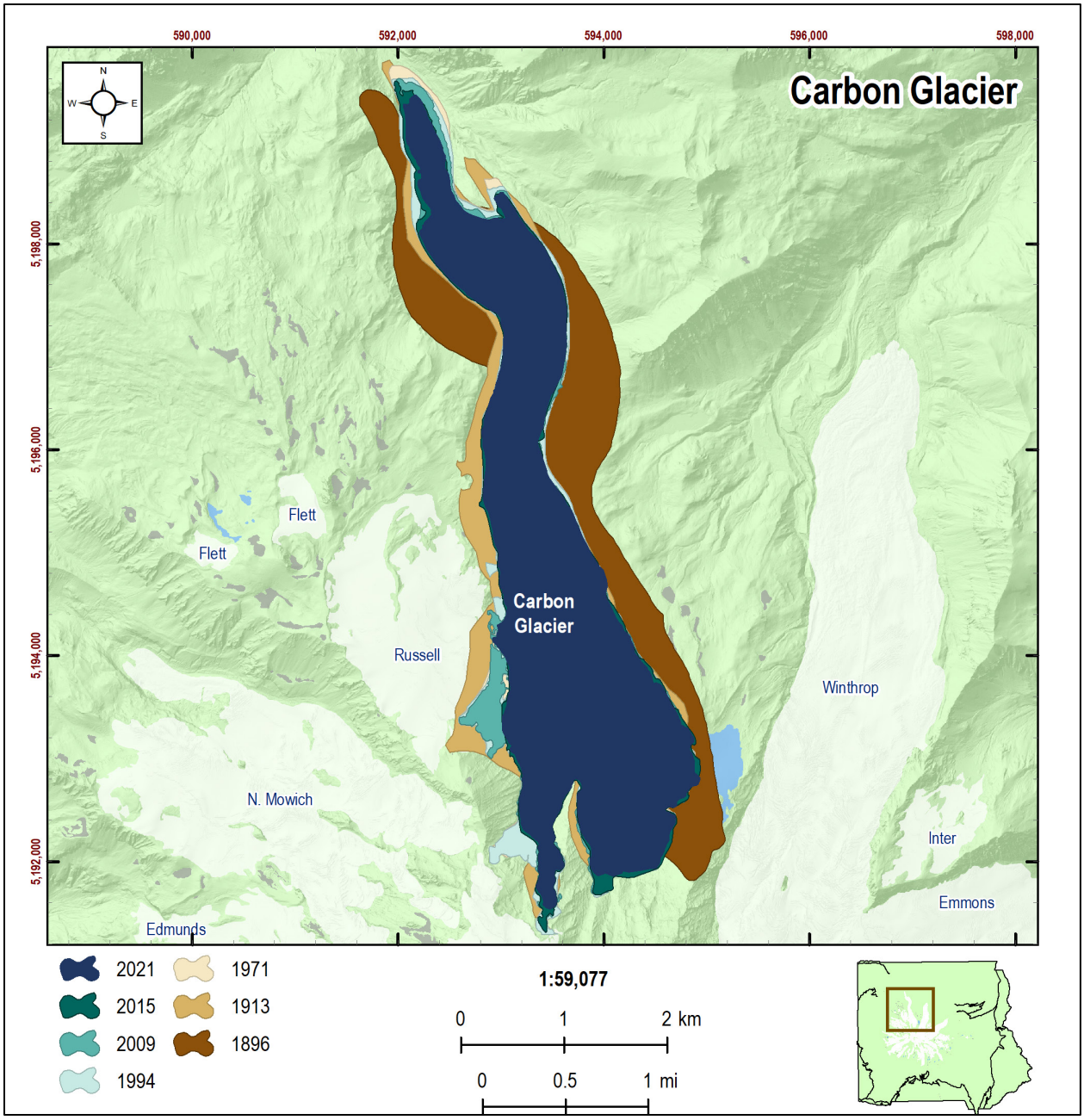


Figure B-1. Detailed map for Carbon Glacier over time.

Table B-1. Observed glacial extent and volume for Carbon Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	8.290	8.455	8.014	7.976	7.454	7.257	7.127
Extent, mi^2	3.201	3.265	3.094	3.080	2.878	2.802	2.752
Volume, km^3	0.6051	0.6216	0.5776	0.5739	0.5231	0.5042	0.4919
Volume, mi^3	0.1452	0.1491	0.1386	0.1377	0.1255	0.1210	0.1180

Table B-2. Observed change in glacial extent (km^2) for Carbon Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	+0.165 (+2.0%)	-0.277 (-3.3%)	-0.314 (-3.8%)	-0.836 (-10.1%)	-1.034 (-12.5%)	-1.163 (-14.0%)
1913	–	-0.442 (-5.2%)	-0.479 (-5.7%)	-1.001 (-11.8%)	-1.199 (-14.2%)	-1.328 (-15.7%)
1971	–	–	-0.038 (-0.5%)	-0.559 (-7.0%)	-0.757 (-9.4%)	-0.887 (-11.1%)
1994	–	–	–	-0.522 (-6.5%)	-0.719 (-9.0%)	-0.849 (-10.6%)
2009	–	–	–	–	-0.198 (-2.7%)	-0.327 (-4.4%)
2015	–	–	–	–	–	-0.130 (-1.8%)

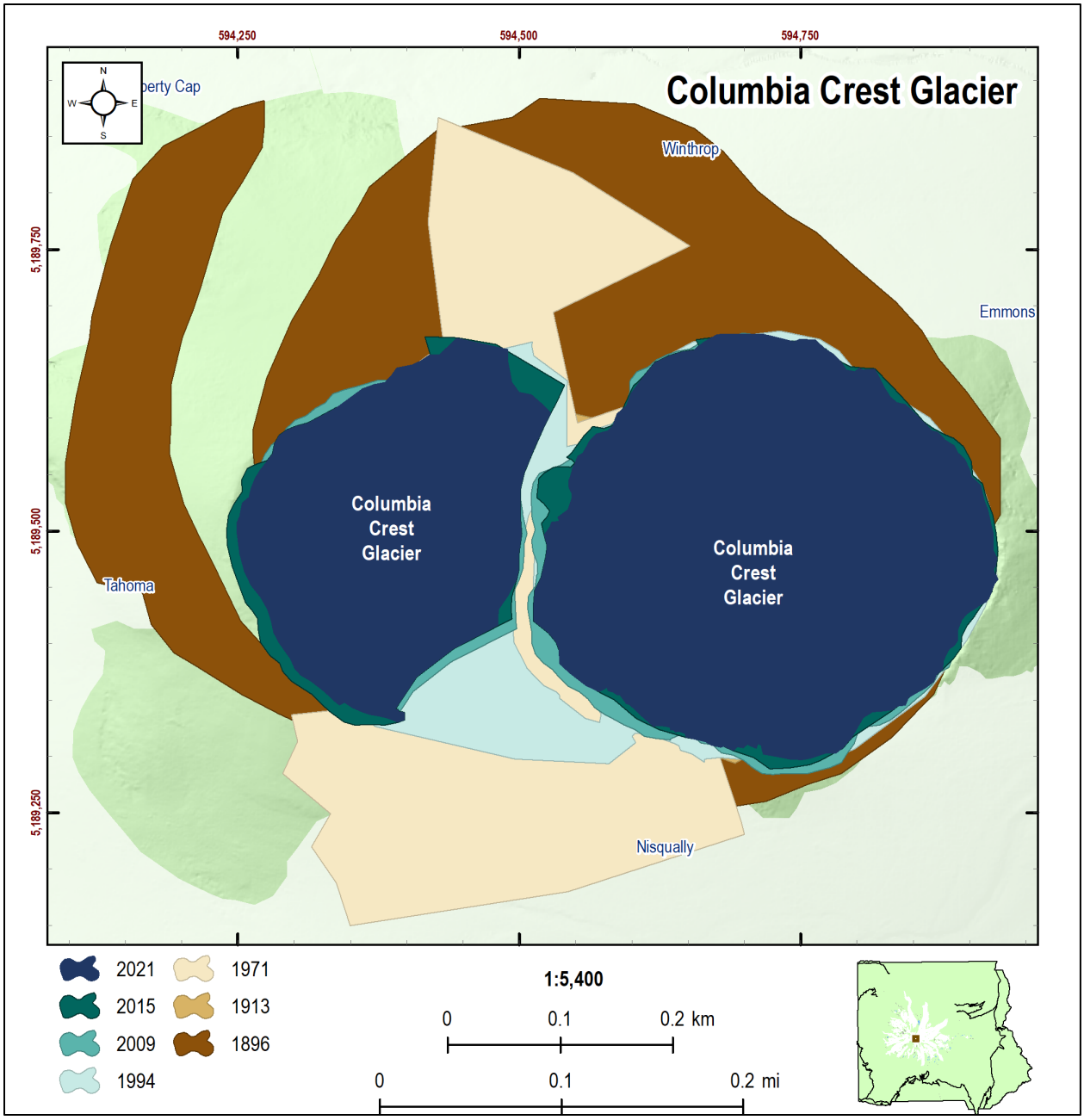


Figure B-2. Detailed map for Columbia Crest Glacier over time.

Table B-3. Observed glacial extent and volume for Columbia Crest Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	0.322	0.107	0.251	0.198	0.118	0.180	0.172
Extent, mi^2	0.124	0.041	0.097	0.076	0.046	0.070	0.067
Volume, km^3	0.0055	0.0012	0.0039	0.0028	0.0014	0.0025	0.0024
Volume, mi^3	0.0013	0.0003	0.0009	0.0007	0.0003	0.0006	0.0006

Table B-4. Observed change in glacial extent (km^2) for Columbia Crest Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	-0.215 (-66.8%)	-0.071 (-22.1%)	-0.124 (-38.6%)	-0.204 (-63.4%)	-0.141 (-43.9%)	-0.149 (-46.5%)
1913	–	+0.144 (+134%)	+0.091 (+84.9%)	+0.011 (+10.4%)	+0.074 (+68.8%)	+0.065 (+61.2%)
1971	–	–	-0.053 (-21.2%)	-0.133 (-53.0%)	-0.070 (-28.0%)	-0.078 (-31.3%)
1994	–	–	–	-0.080 (-40.3%)	-0.017 (-8.7%)	-0.025 (-12.8%)
2009	–	–	–	–	+0.062 (+53.0%)	+0.054 (+46.1%)
2015	–	–	–	–	–	-0.008 (-4.5%)

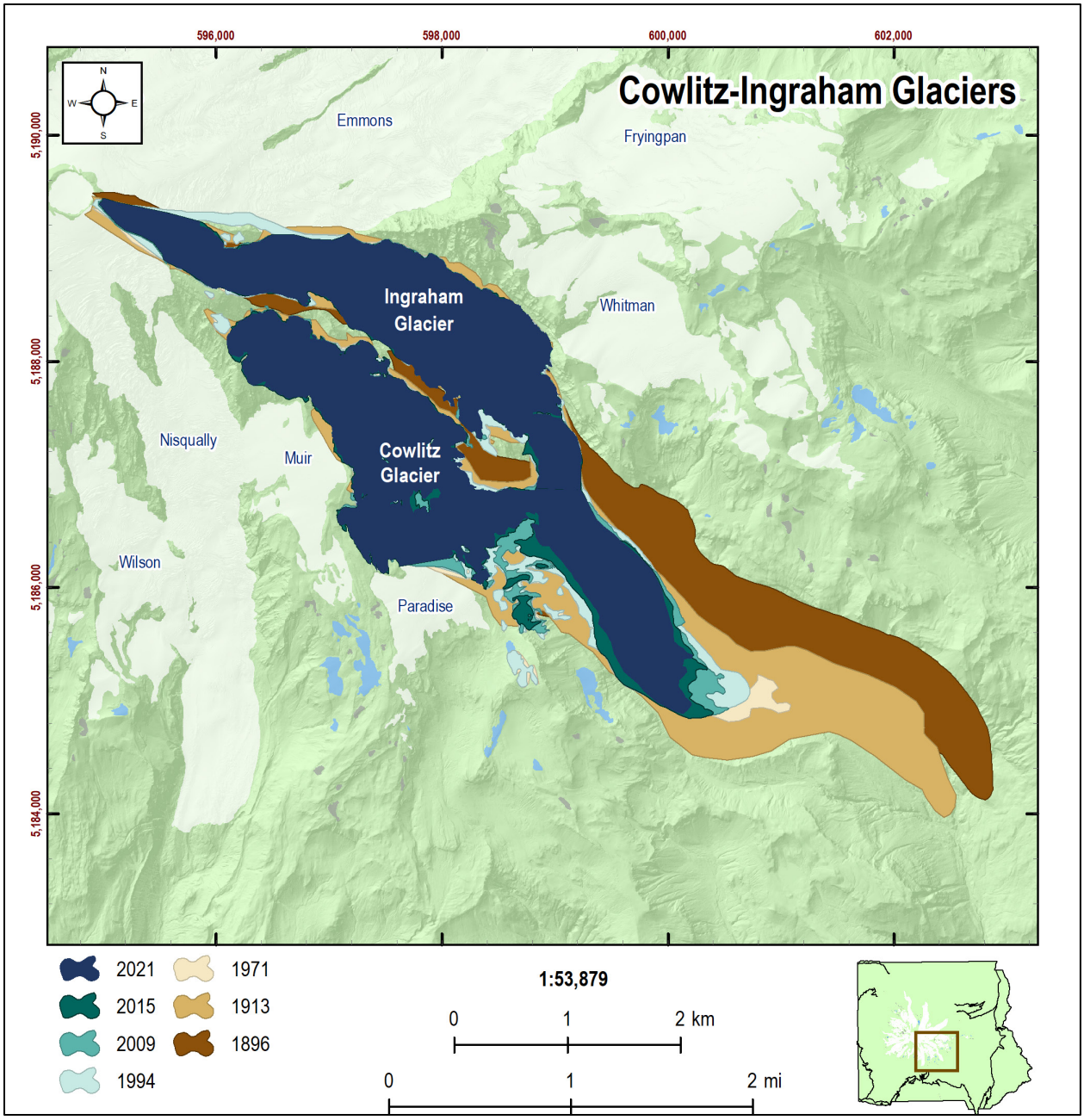


Figure B-3. Detailed map for Cowlitz-Ingraham Glaciers over time.

Table B-5. Observed glacial extent and volume for Cowlitz-Ingraham Glaciers over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	8.310	9.838	7.639	7.697	7.048	6.998	6.647
Extent, mi^2	3.208	3.798	2.950	2.972	2.721	2.702	2.566
Volume, km^3	0.5151	0.6490	0.4591	0.4639	0.4112	0.3137	0.2917
Volume, mi^3	0.1236	0.1557	0.1102	0.1113	0.0986	0.0753	0.0700

Table B-6. Observed change in glacial extent (km^2) for Cowlitz-Ingraham Glaciers over time.

Year	1913	1971	1994	2009	2015	2021
1896	+1.528 (+18.4%)	-0.670 (-8.1%)	-0.613 (-7.4%)	-1.262 (-15.2%)	-1.312 (-15.8%)	-1.663 (-20.0%)
1913	–	-2.199 (-22.3%)	-2.141 (-21.8%)	-2.790 (-28.4%)	-2.840 (-28.9%)	-3.191 (-32.4%)
1971	–	–	+0.058 (+0.8%)	-0.592 (-7.7%)	-0.642 (-8.4%)	-0.992 (-13.0%)
1994	–	–	–	-0.649 (-8.4%)	-0.699 (-9.1%)	-1.050 (-13.6%)
2009	–	–	–	–	-0.050 (-0.7%)	-0.401 (-5.7%)
2015	–	–	–	–	–	-0.351 (-5.0%)

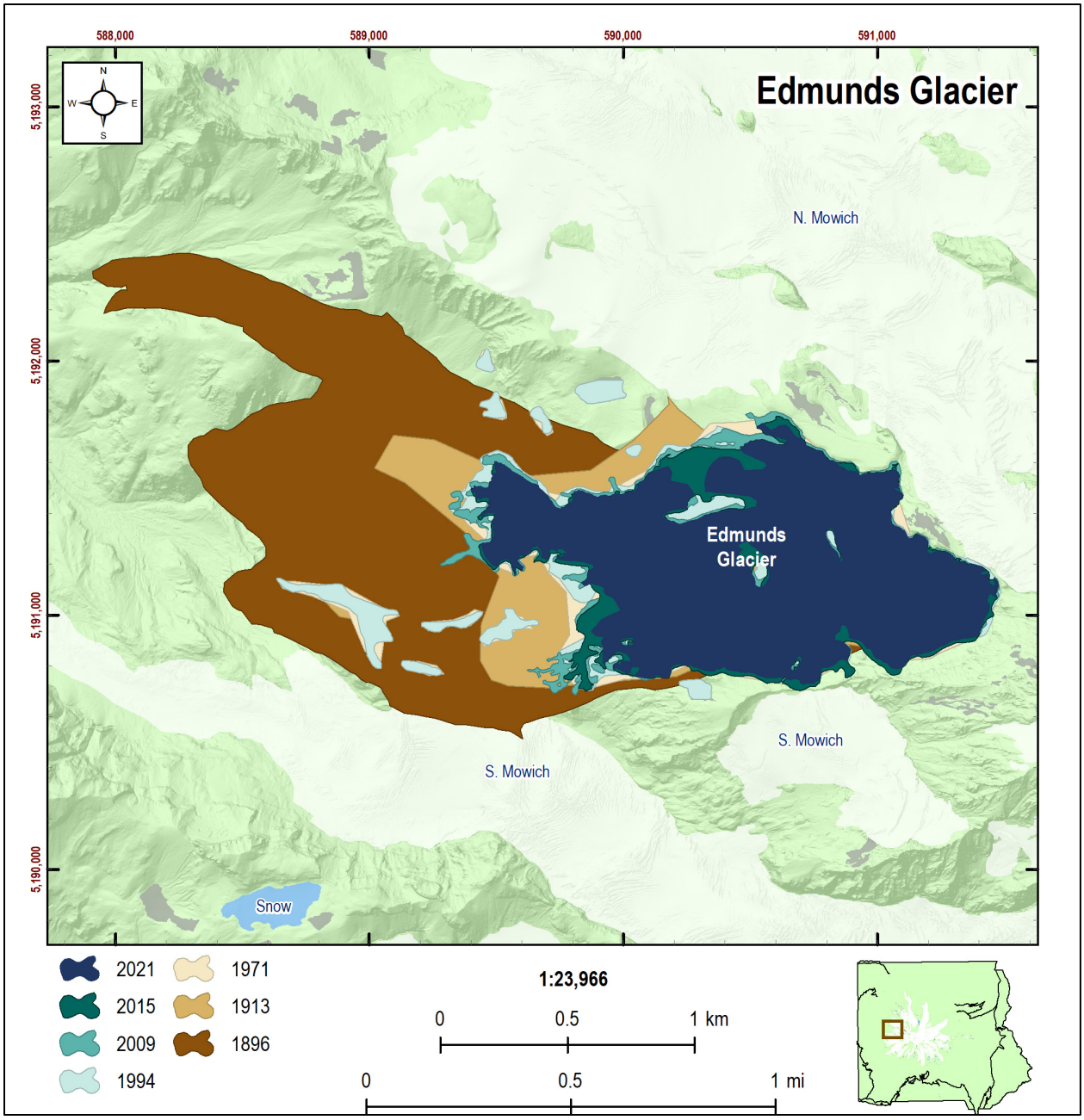


Figure B-4. Detailed map for Edmunds Glacier over time.

Table B-7. Observed glacial extent and volume for Edmunds Glacier over time over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	2.820	1.530	1.474	1.417	1.300	1.252	1.165
Extent, mi^2	1.089	0.591	0.569	0.547	0.502	0.484	0.450
Volume, km^3	0.0933	0.0404	0.0384	0.0364	0.0324	0.0308	0.0279
Volume, mi^3	0.0224	0.0097	0.0092	0.0087	0.0078	0.0074	0.0067

Table B-8. Observed change in glacial extent (km^2) for Edmunds Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	-1.290 (-45.7%)	-1.346 (-47.7%)	-1.403 (-49.8%)	-1.520 (-53.9%)	-1.567 (-55.6%)	-1.655 (-58.7%)
1913	–	-0.056 (-3.7%)	-0.113 (-7.4%)	-0.230 (-15.0%)	-0.278 (-18.1%)	-0.365 (-23.9%)
1971	–	–	-0.057 (-3.9%)	-0.174 (-11.8%)	-0.221 (-15.0%)	-0.309 (-21.0%)
1994	–	–	–	-0.117 (-8.2%)	-0.164 (-11.6%)	-0.252 (-17.8%)
2009	–	–	–	–	-0.048 (-3.7%)	-0.135 (-10.4%)
2015	–	–	–	–	–	-0.088 (-7.0%)

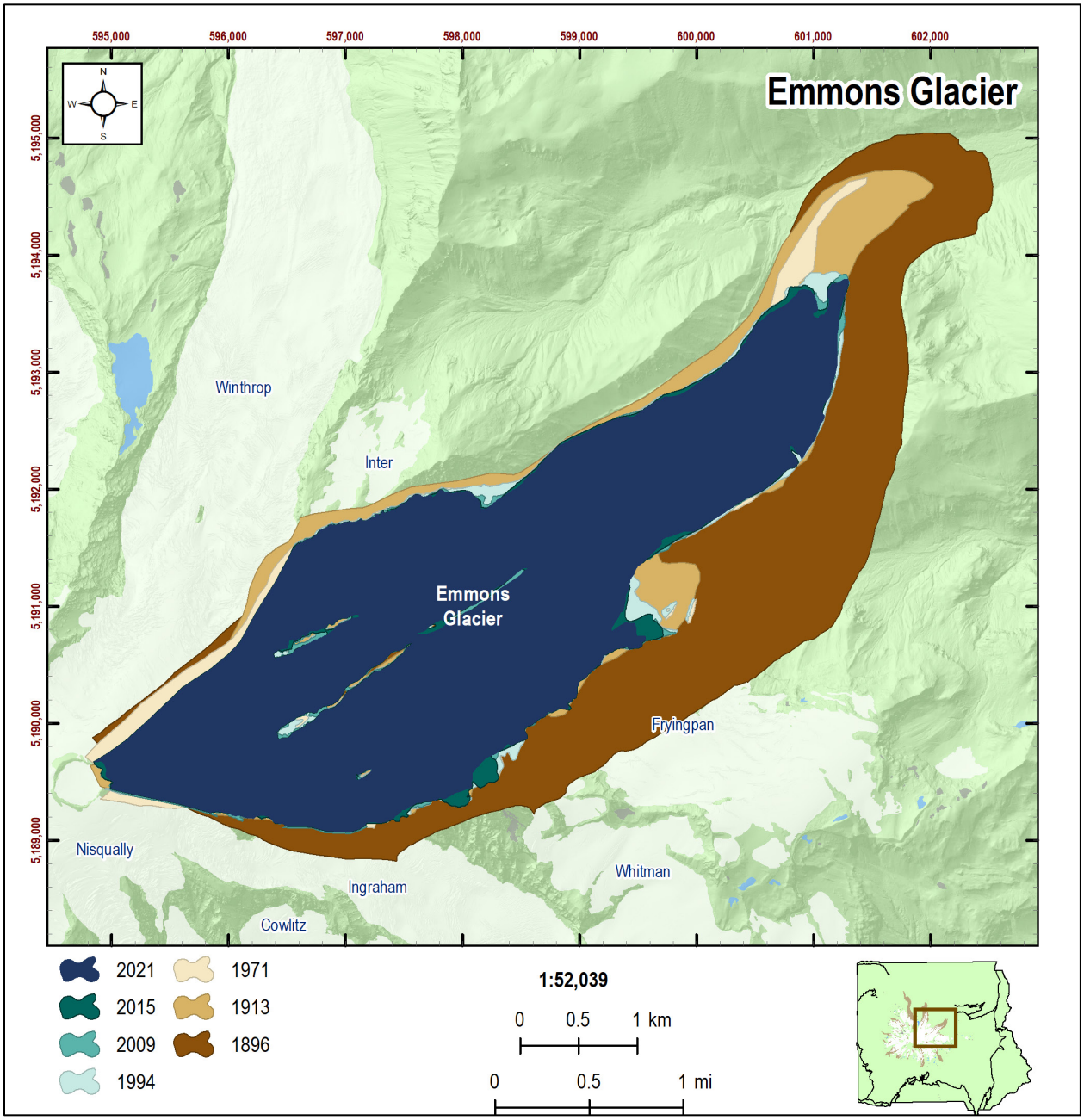


Figure B-5. Detailed map for Emmons Glacier over time.

Table B-9. Observed glacial extent and volume for Emmons Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	17.458	12.622	11.158	11.223	10.979	11.027	10.959
Extent, mi^2	6.741	4.873	4.308	4.333	4.239	4.258	4.231
Volume, km^3	1.2461	0.7997	0.6757	0.6810	0.6608	0.6648	0.6592
Volume, mi^3	0.2990	0.1919	0.1621	0.1634	0.1585	0.1595	0.1582

Table B-10. Observed change in glacial extent (km^2) for Emmons Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	-4.836 (-27.7%)	-6.299 (-36.1%)	-6.235 (-35.7%)	-6.479 (-37.1%)	-6.431 (-36.8%)	-6.499 (-37.2%)
1913	–	-1.464 (-11.6%)	-1.400 (-11.1%)	-1.643 (-13.0%)	-1.595 (-12.6%)	-1.663 (-13.2%)
1971	–	–	+0.064 (+0.6%)	-0.179 (-1.6%)	-0.131 (-1.2%)	-0.199 (-1.8%)
1994	–	–	–	-0.243 (-2.2%)	-0.196 (-1.7%)	-0.263 (-2.3%)
2009	–	–	–	–	+0.048 (+0.4%)	-0.020 (-0.2%)
2015	–	–	–	–	–	-0.068 (-0.6%)

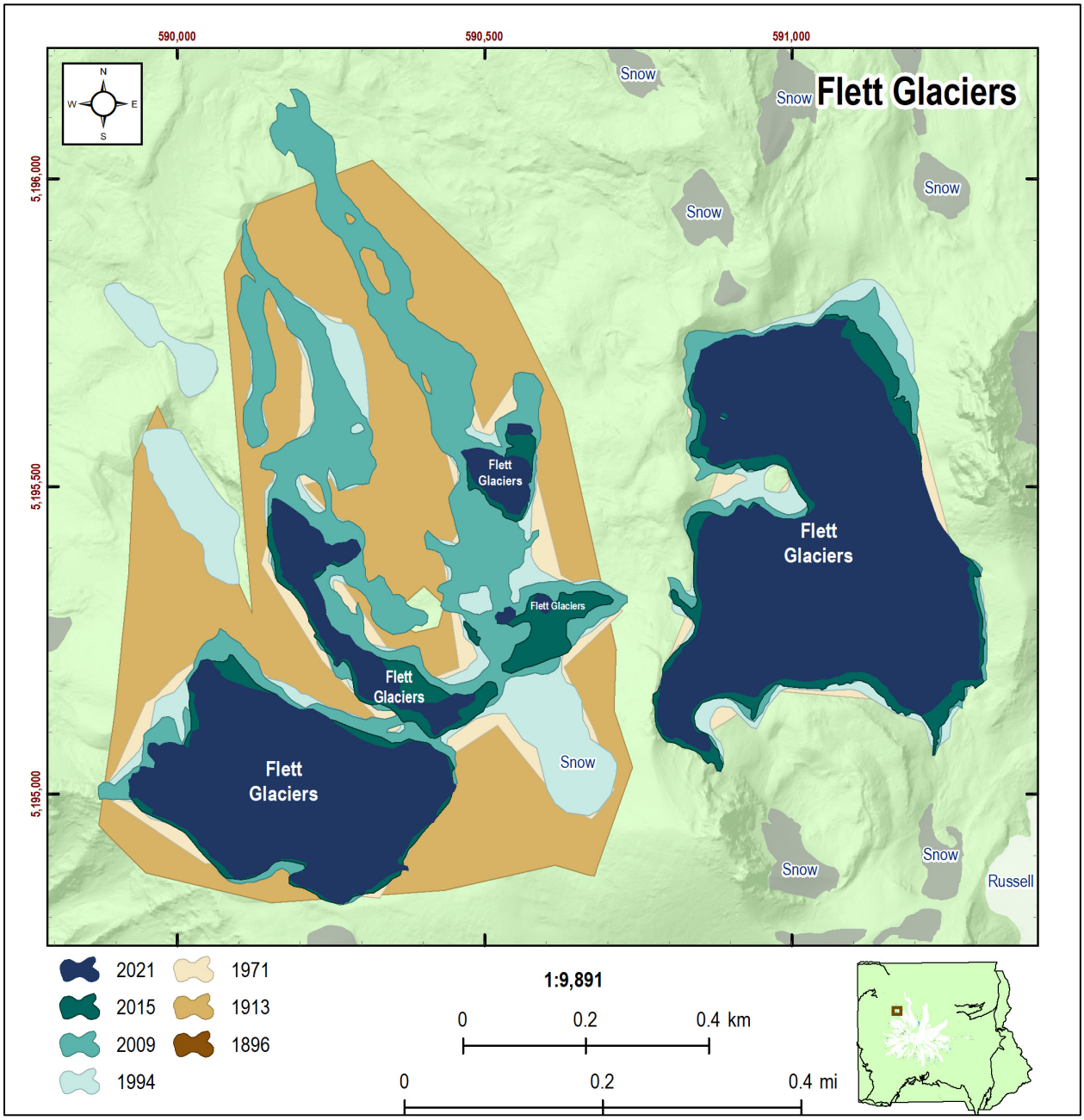


Figure B-6. Detailed map for Flett Glaciers over time.

Table B-11. Observed glacial extent and volume for Flett Glaciers over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	---	0.737	0.576	0.615	0.582	0.406	0.363
Extent, mi^2	---	0.284	0.223	0.238	0.225	0.157	0.140
Volume, km^3	---	0.0183	0.0131	0.0143	0.0132	0.0081	0.0069
Volume, mi^3	---	0.0044	0.0031	0.0034	0.0032	0.0019	0.0017

Table B-12. Observed change in glacial extent (km^2) for Flett Glaciers over time.

Year	1913	1971	1994	2009	2015	2021
1896	–	–	–	–	–	–
1913	–	-0.160 (-21.7%)	-0.121 (-16.5%)	-0.155 (-21.0%)	-0.331 (-44.9%)	-0.374 (-50.7%)
1971	–	–	+0.039 (+6.8%)	+0.006 (+1.0%)	-0.171 (-29.6%)	-0.214 (-37.0%)
1994	–	–	–	-0.033 (-5.4%)	-0.210 (-34.1%)	-0.252 (-41.0%)
2009	–	–	–	–	-0.176 (-30.3%)	-0.219 (-37.6%)
2015	–	–	–	–	–	-0.043 (-10.5%)

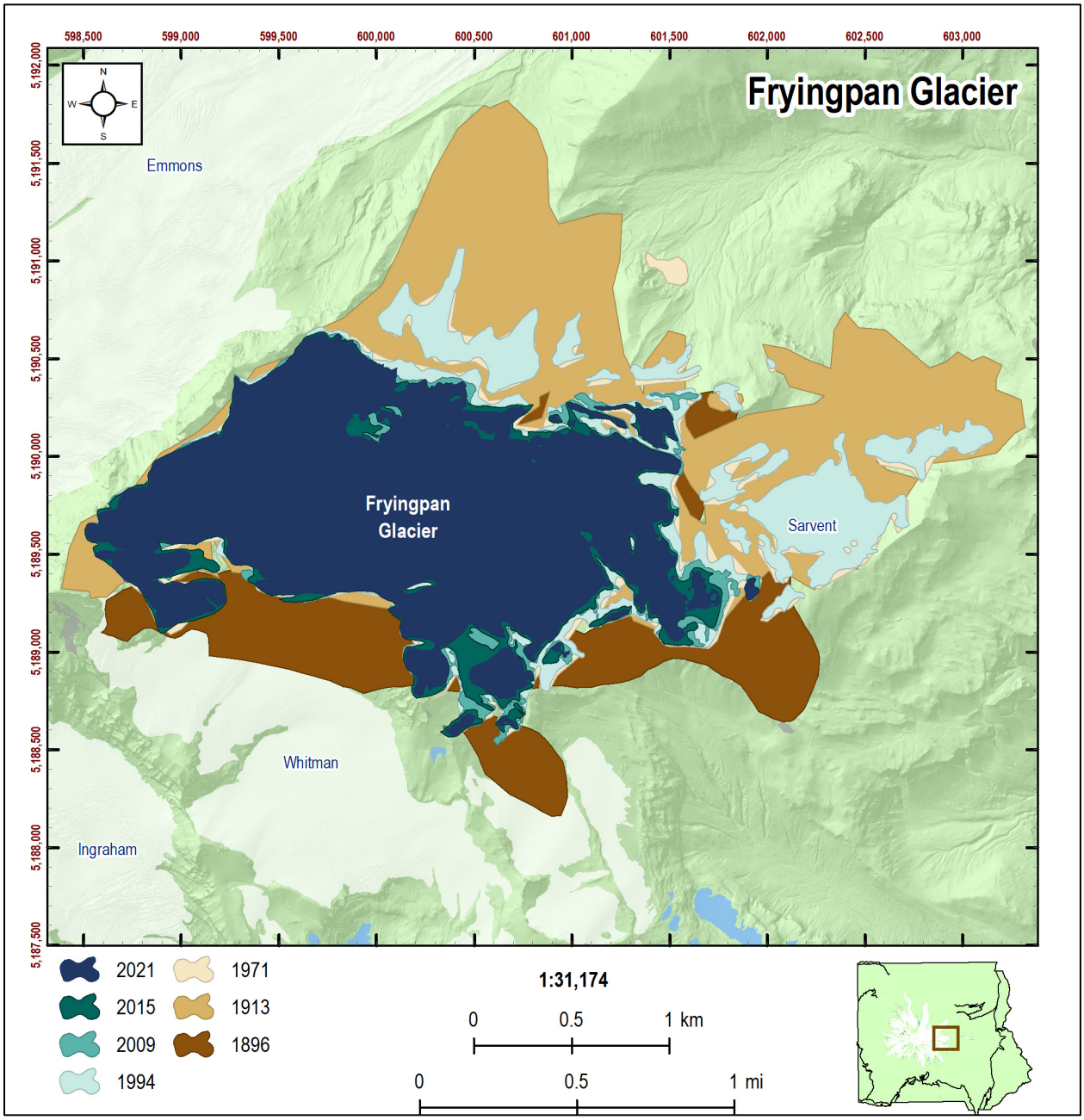


Figure B-7. Detailed map for Fryingpan Glacier over time.

Table B-13. Observed glacial extent and volume for Fryingpan Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	3.722	6.121	4.339	4.231	3.297	3.245	2.993
Extent, mi^2	1.437	2.363	1.675	1.634	1.273	1.253	1.156
Volume, km^3	0.1252	0.2470	0.1544	0.1492	0.1061	0.1038	0.093
Volume, mi^3	0.0300	0.0593	0.0370	0.0358	0.0255	0.0249	0.0223

Table B-14. Observed change in glacial extent (km^2) for Fryingpan Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	+2.399 (+64.5%)	+0.617 (+16.6%)	+0.509 (+13.7%)	-0.425 (-11.4%)	-0.477 (-12.8%)	-0.728 (-19.6%)
1913	–	-1.782 (-29.1%)	-1.890 (-30.9%)	-2.824 (-46.1%)	-2.876 (-47.0%)	-3.127 (-51.1%)
1971	–	–	-0.108 (-2.5%)	-1.042 (-24.0%)	-1.094 (-25.2%)	-1.345 (-31.0%)
1994	–	–	–	-0.934 (-22.1%)	-0.986 (-23.3%)	-1.238 (-29.3%)
2009	–	–	–	–	-0.052 (-1.6%)	-0.303 (-9.2%)
2015	–	–	–	–	–	-0.251 (-7.7%)

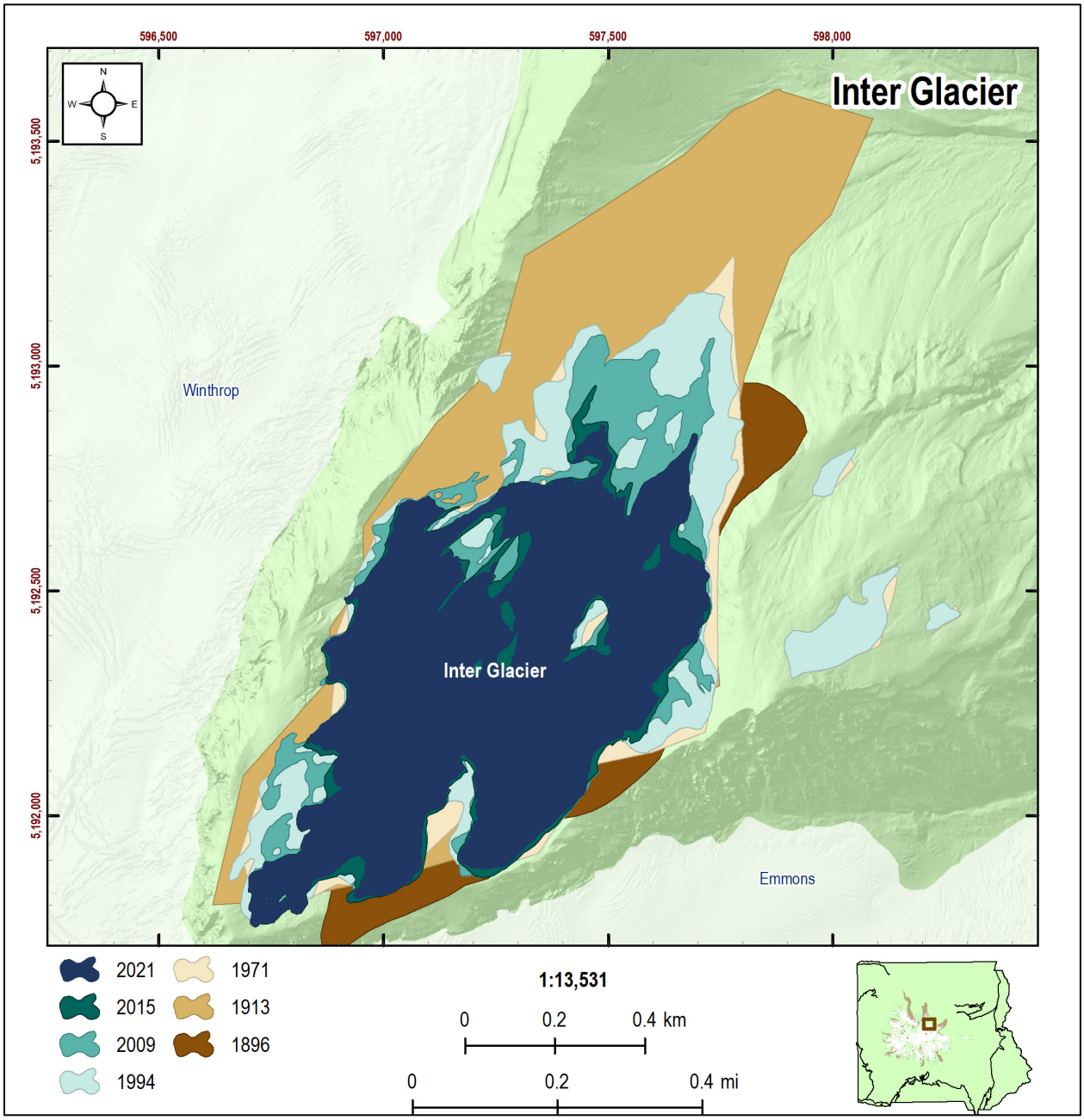


Figure B-8. Detailed map for over time Inter Glacier.

Table B-15. Observed glacial extent and volume for Inter Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	0.570	1.143	0.836	0.826	0.665	0.574	0.532
Extent, mi^2	0.220	0.441	0.323	0.319	0.257	0.222	0.206
Volume, km^3	0.0115	0.0297	0.0193	0.0190	0.0141	0.0116	0.0104
Volume, mi^3	0.0027	0.0071	0.0046	0.0046	0.0034	0.0028	0.0025

Table B-16. Observed change in glacial extent (km^2) for Inter Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	+0.573 (+100%)	+0.266 (+46.6%)	+0.255 (+44.8%)	+0.095 (+16.7%)	+0.004 (+0.7%)	-0.038 (-6.6%)
1913	–	-0.307 (-26.9%)	-0.318 (-27.8%)	-0.478 (-41.8%)	-0.569 (-49.8%)	-0.611 (-53.4%)
1971	–	–	-0.010 (-1.2%)	-0.171 (-20.4%)	-0.262 (-31.3%)	-0.303 (-36.3%)
1994	–	–	–	-0.160 (-19.4%)	-0.252 (-30.5%)	-0.293 (-35.5%)
2009	–	–	–	–	-0.091 (-13.7%)	-0.133 (-20.0%)
2015	–	–	–	–	–	-0.042 (-7.2%)

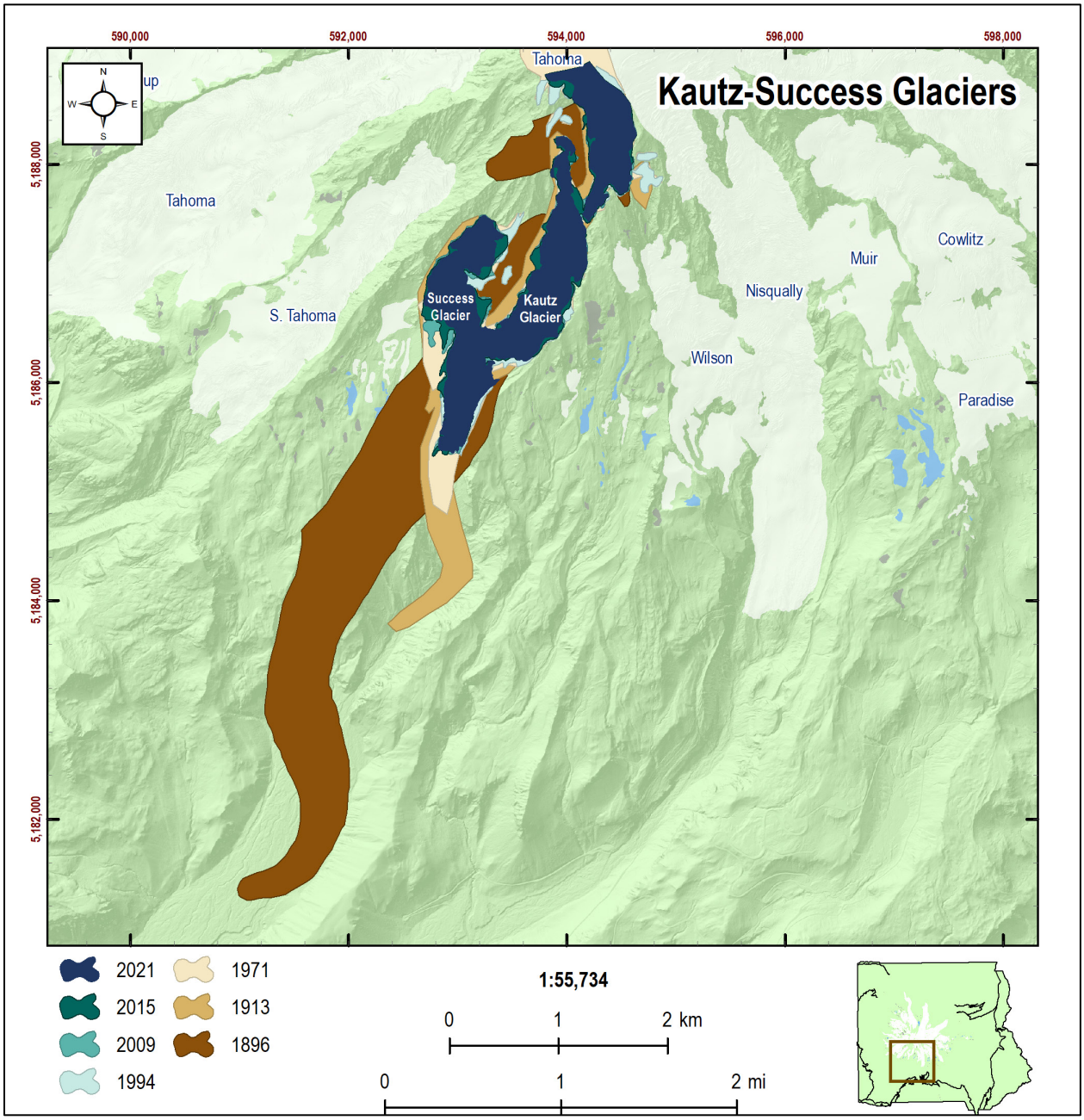


Figure B-9. Detailed map for Kautz-Success Glaciers over time.

Table B-17. Observed glacial extent and volume for Kautz-Success Glaciers over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	5.174	3.028	2.728	2.201	2.125	2.081	1.957
Extent, mi^2	1.998	1.169	1.053	0.850	0.821	0.803	0.756
Volume, km^3	0.2644	0.1048	0.0890	0.0647	0.0783	0.0623	0.0582
Volume, mi^3	0.0634	0.0251	0.0213	0.0155	0.0188	0.0150	0.0140

Table B-18. Observed change in glacial extent (km^2) for Kautz-Success Glaciers over time.

Year	1913	1971	1994	2009	2015	2021
1896	-2.146 (-41.5%)	-2.446 (-47.3%)	-2.973 (-57.5%)	-3.049 (-58.9%)	-3.093 (-59.8%)	-3.217 (-62.2%)
1913	–	-0.300 (-9.9%)	-0.827 (-27.3%)	-0.903 (-29.8%)	-0.947 (-31.3%)	-1.071 (-35.4%)
1971	–	–	-0.527 (-19.3%)	-0.603 (-22.1%)	-0.647 (-23.7%)	-0.771 (-28.3%)
1994	–	–	–	-0.076 (-3.4%)	-0.120 (-5.5%)	-0.244 (-11.1%)
2009	–	–	–	–	-0.044 (-2.1%)	-0.168 (-7.9%)
2015	–	–	–	–	–	-0.124 (-5.9%)

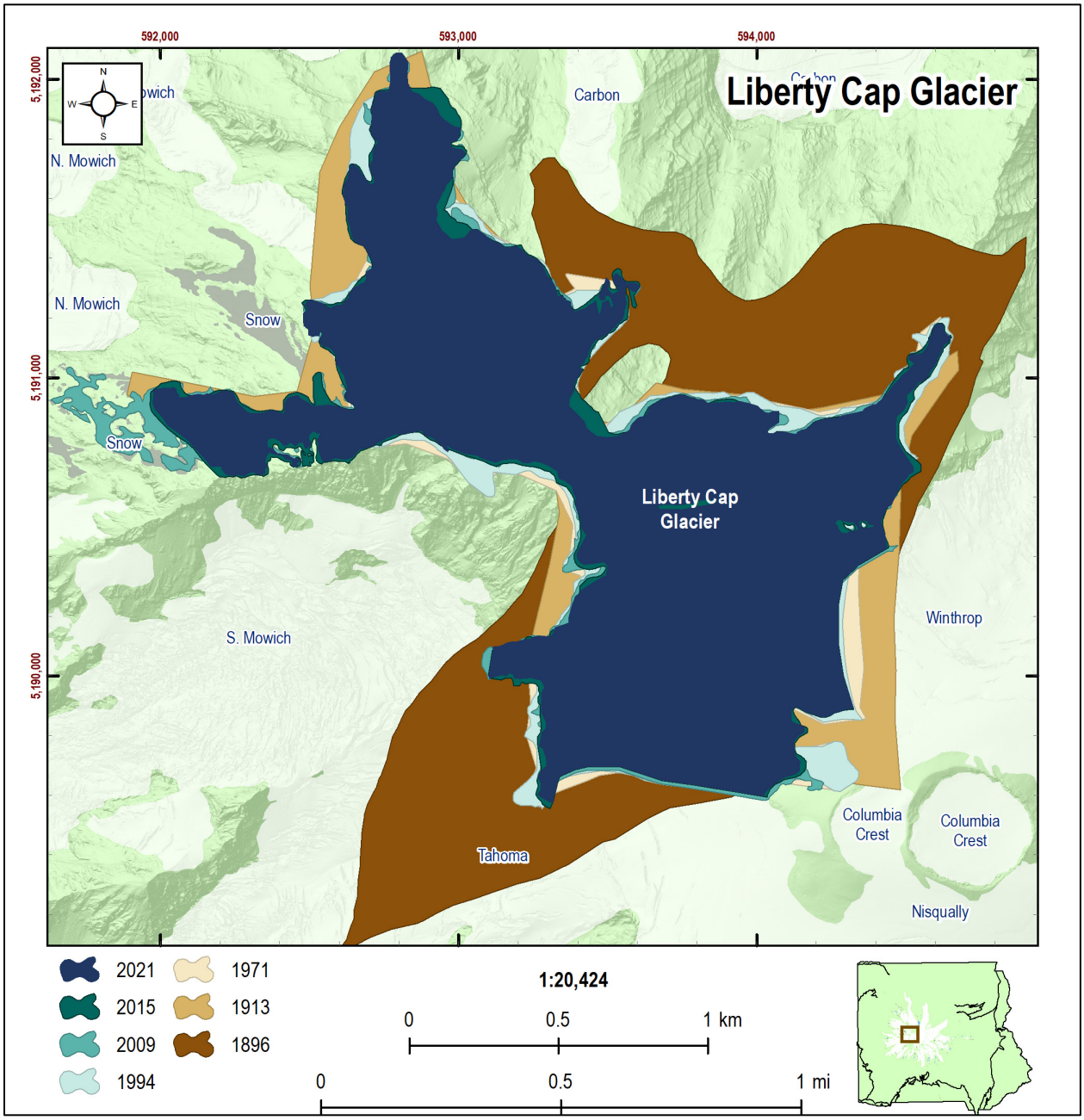


Figure B-10. Detailed map for Liberty Cap Glacier over time.

Table B-19. Observed glacial extent and volume for Liberty Cap Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	2.822	2.401	2.079	2.102	2.200	2.139	2.076
Extent, mi^2	1.090	0.927	0.803	0.812	0.849	0.826	0.801
Volume, km^3	0.1269	0.1017	0.0835	0.0848	0.0902	0.0868	0.0833
Volume, mi^3	0.0304	0.0244	0.0200	0.0203	0.0216	0.0208	0.0200

Table B-20. Observed change in glacial extent (km^2) for Liberty Cap Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	-0.422 (-14.9%)	-0.743 (-26.3%)	-0.721 (-25.5%)	-0.623 (-22.1%)	-0.684 (-24.2%)	-0.747 (-26.5%)
1913	–	-0.321 (-13.4%)	-0.299 (-12.4%)	-0.201 (-8.4%)	-0.262 (-10.9%)	-0.325 (-13.5%)
1971	–	–	+0.023 (+1.1%)	+0.120 (+5.8%)	+0.059 (+2.9%)	-0.004 (-0.2%)
1994	–	–	–	+0.098 (+4.7%)	+0.037 (+1.8%)	-0.026 (-1.2%)
2009	–	–	–	–	-0.061 (-2.8%)	-0.124 (-5.6%)
2015	–	–	–	–	–	-0.063 (-2.9%)

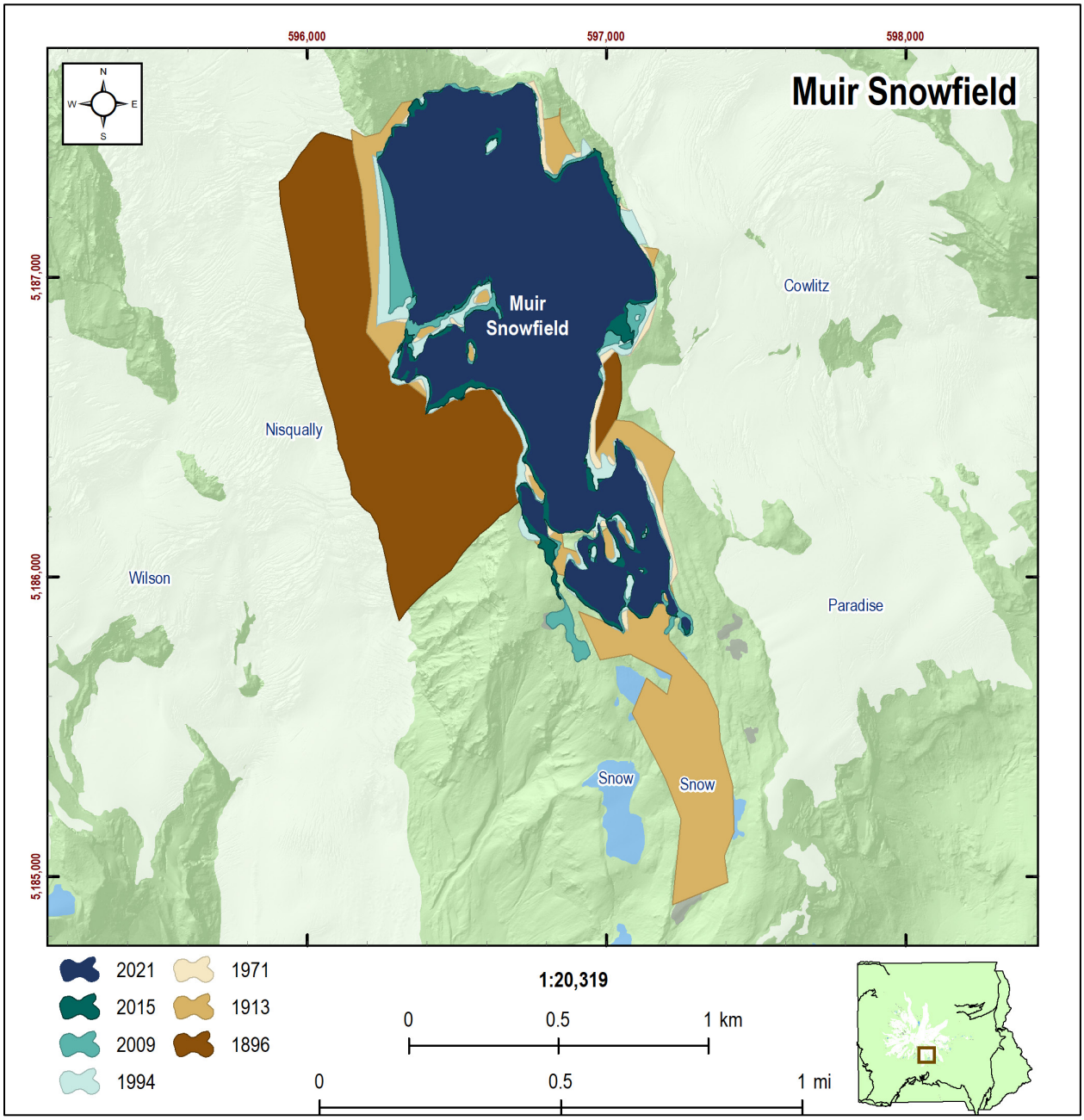


Figure B-11. Detailed map for Muir Snowfield over time.

Table B-21. Observed glacial extent and volume for Muir Snowfield over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	1.132	1.216	0.968	0.977	0.920	0.875	0.823
Extent, mi^2	0.437	0.469	0.374	0.377	0.355	0.338	0.318
Volume, km^3	0.0279	0.0308	0.0225	0.0228	0.021	0.0196	0.018
Volume, mi^3	0.0067	0.0074	0.0054	0.0055	0.005	0.0047	0.0043

Table B-22. Observed change in glacial extent (km^2) for Muir Snowfield over time.

Year	1913	1971	1994	2009	2015	2021
1896	+0.084 (+7.4%)	-0.164 (-14.5%)	-0.155 (-13.7%)	-0.212 (-18.7%)	-0.257 (-22.7%)	-0.309 (-27.3%)
1913	–	-0.248 (-20.4%)	-0.239 (-19.7%)	-0.296 (-24.3%)	-0.340 (-28.0%)	-0.393 (-32.3%)
1971	–	–	+0.009 (+0.9%)	-0.048 (-5.0%)	-0.093 (-9.6%)	-0.145 (-15.0%)
1994	–	–	–	-0.057 (-5.8%)	-0.101 (-10.4%)	-0.154 (-15.8%)
2009	–	–	–	–	-0.045 (-4.9%)	-0.097 (-10.6%)
2015	–	–	–	–	–	-0.053 (-6.0%)

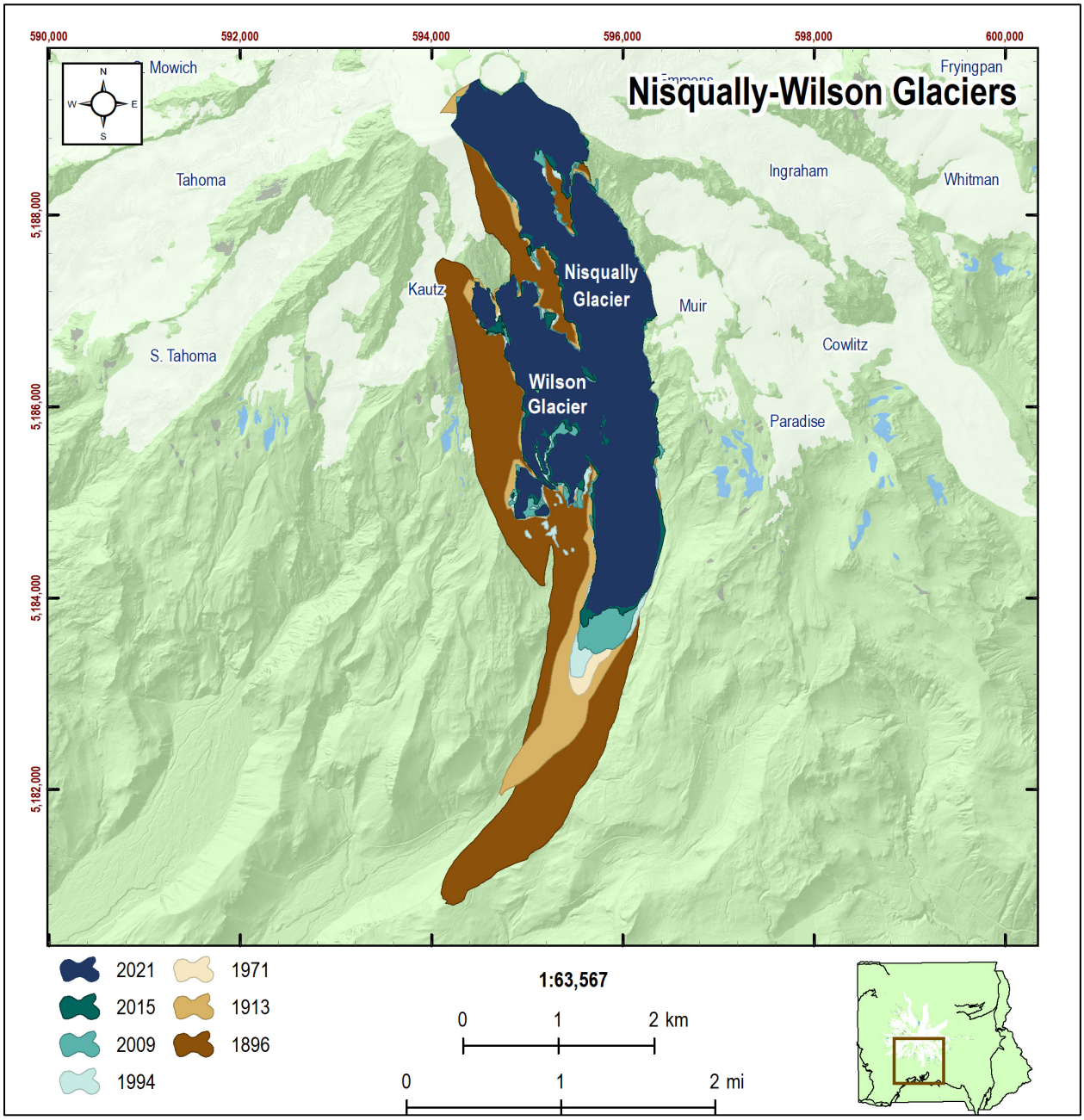


Figure B-12. Detailed map for Nisqually-Wilson Glaciers over time.

Table B-23. Observed glacial extent and volume for Nisqually-Wilson Glaciers over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	10.026	6.588	6.072	6.254	6.003	5.754	5.562
Extent, mi^2	3.871	2.544	2.344	2.415	2.318	2.222	2.147
Volume, km^3	0.6139	0.3456	0.3091	0.3219	0.3043	0.2397	0.2295
Volume, mi^3	0.1473	0.0829	0.0742	0.0772	0.0730	0.0575	0.0551

Table B-24. Observed change in glacial extent (km^2) for Nisqually-Wilson Glaciers over time.

Year	1913	1971	1994	2009	2015	2021
1896	-3.438 (-34.3%)	-3.954 (-39.4%)	-3.772 (-37.6%)	-4.023 (-40.1%)	-4.272 (-42.6%)	-4.465 (-44.5%)
1913	–	-0.516 (-7.8%)	-0.334 (-5.1%)	-0.585 (-8.9%)	-0.834 (-12.7%)	-1.026 (-15.6%)
1971	–	–	+0.182 (+3.0%)	-0.069 (-1.1%)	-0.318 (-5.2%)	-0.510 (-8.4%)
1994	–	–	–	-0.251 (-4.0%)	-0.500 (-8.0%)	-0.692 (-11.1%)
2009	–	–	–	–	-0.249 (-4.2%)	-0.441 (-7.4%)
2015	–	–	–	–	–	-0.192 (-3.3%)

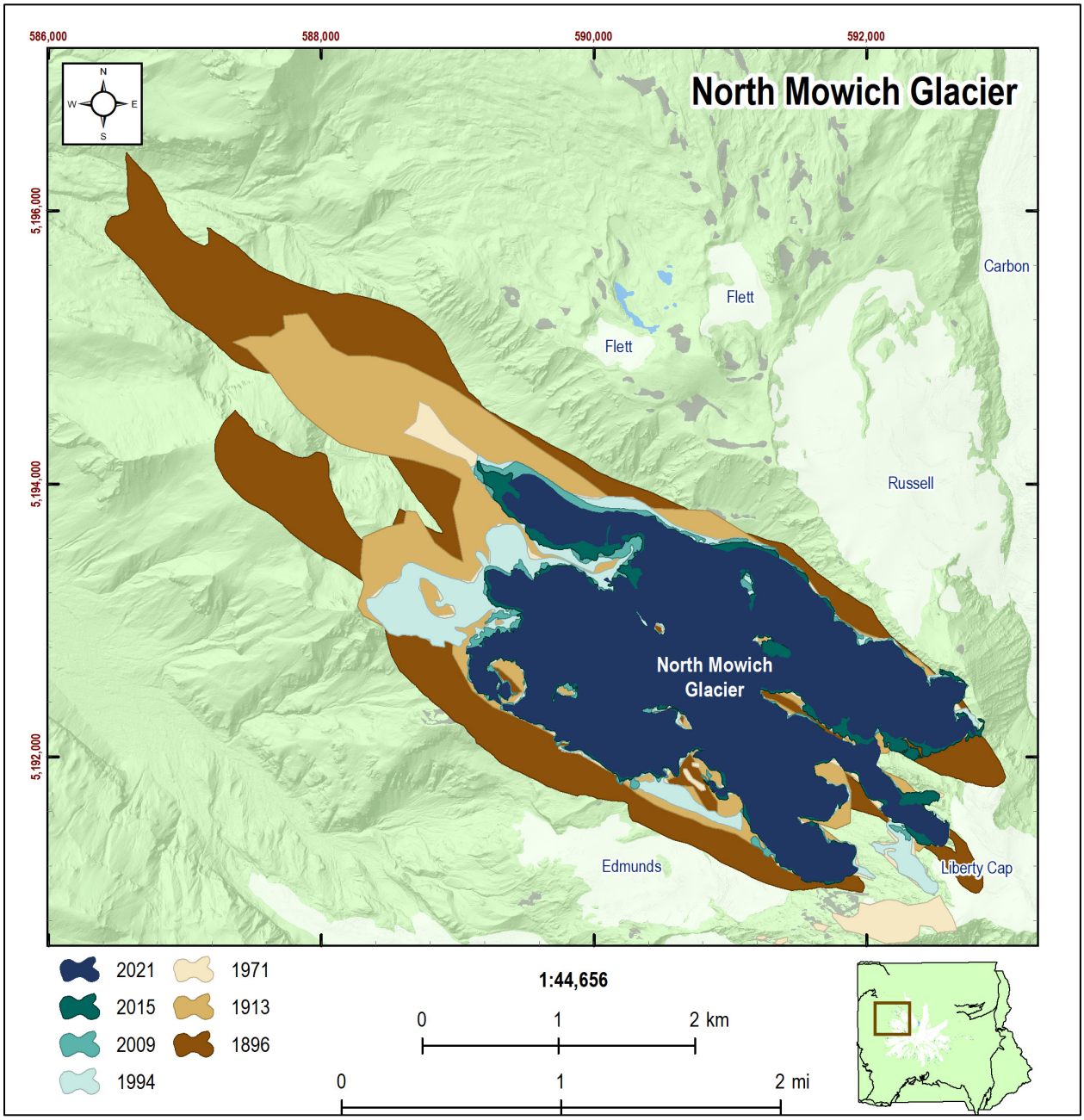


Figure B-13. Detailed map for North Mowich Glacier over time.

Table B-25. Observed glacial extent and volume for North Mowich Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	11.074	8.032	6.261	6.108	5.207	5.144	4.907
Extent, mi^2	4.276	3.101	2.417	2.358	2.010	1.986	1.895
Volume, km^3	0.6363	0.4102	0.2918	0.2821	0.2268	0.2231	0.2091
Volume, mi^3	0.1526	0.0984	0.0700	0.0677	0.0544	0.0535	0.0502

Table B-26. Observed change in glacial extent (km^2) for North Mowich Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	-3.042 (-27.5%)	-4.813 (-43.5%)	-4.966 (-44.8%)	-5.868 (-53.0%)	-5.930 (-53.5%)	-6.167 (-55.7%)
1913	–	-1.772 (-22.1%)	-1.924 (-24.0%)	-2.826 (-35.2%)	-2.888 (-36.0%)	-3.125 (-38.9%)
1971	–	–	-0.153 (-2.4%)	-1.054 (-16.8%)	-1.117 (-17.8%)	-1.354 (-21.6%)
1994	–	–	–	-0.902 (-14.8%)	-0.964 (-15.8%)	-1.201 (-19.7%)
2009	–	–	–	–	-0.062 (-1.2%)	-0.300 (-5.8%)
2015	–	–	–	–	–	-0.237 (-4.6%)

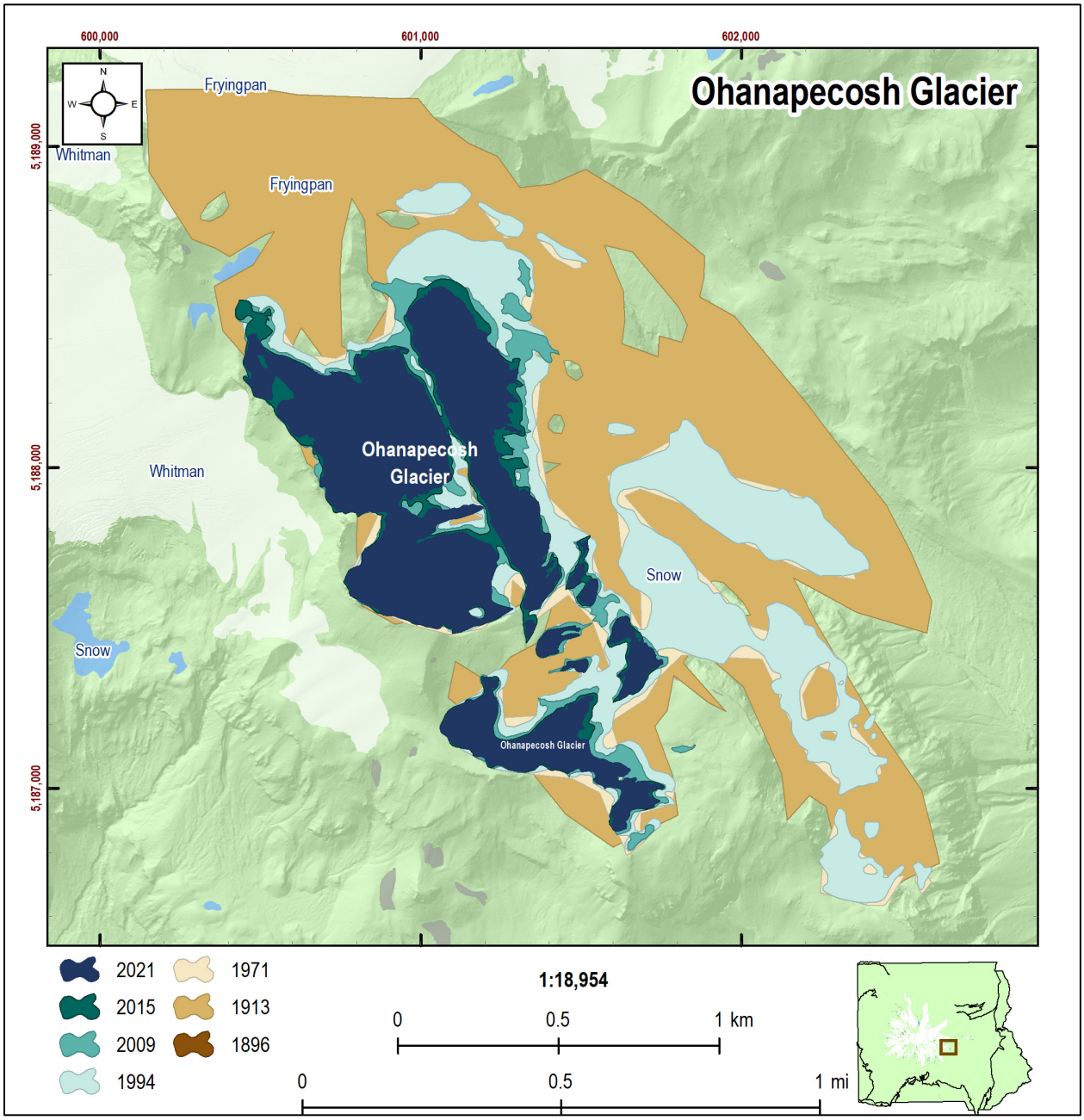


Figure B-14. Detailed map for over time Ohanapecosh Glacier.

Table B-27. Observed glacial extent and volume for Ohanapecosh Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	–	2.968	1.369	1.389	0.786	0.669	0.616
Extent, mi^2	–	1.146	0.529	0.536	0.303	0.258	0.238
Volume, km^3	–	0.0987	0.0343	0.0350	0.0161	0.0129	0.0115
Volume, mi^3	–	0.0237	0.0082	0.0084	0.0039	0.0031	0.0028

Table B-28. Observed change in glacial extent (km^2) for Ohanapecosh Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	–	–	–	–	–	–
1913	–	-1.598 (-53.9%)	-1.579 (-53.2%)	-2.182 (-73.5%)	-2.299 (-77.5%)	-2.352 (-79.3%)
1971	–	–	+0.019 (+1.4%)	-0.584 (-42.6%)	-0.700 (-51.2%)	-0.754 (-55.0%)
1994	–	–	–	-0.603 (-43.4%)	-0.720 (-51.8%)	-0.773 (-55.7%)
2009	–	–	–	–	-0.117 (-14.8%)	-0.170 (-21.6%)
2015	–	–	–	–	–	-0.053 (-8.0%)

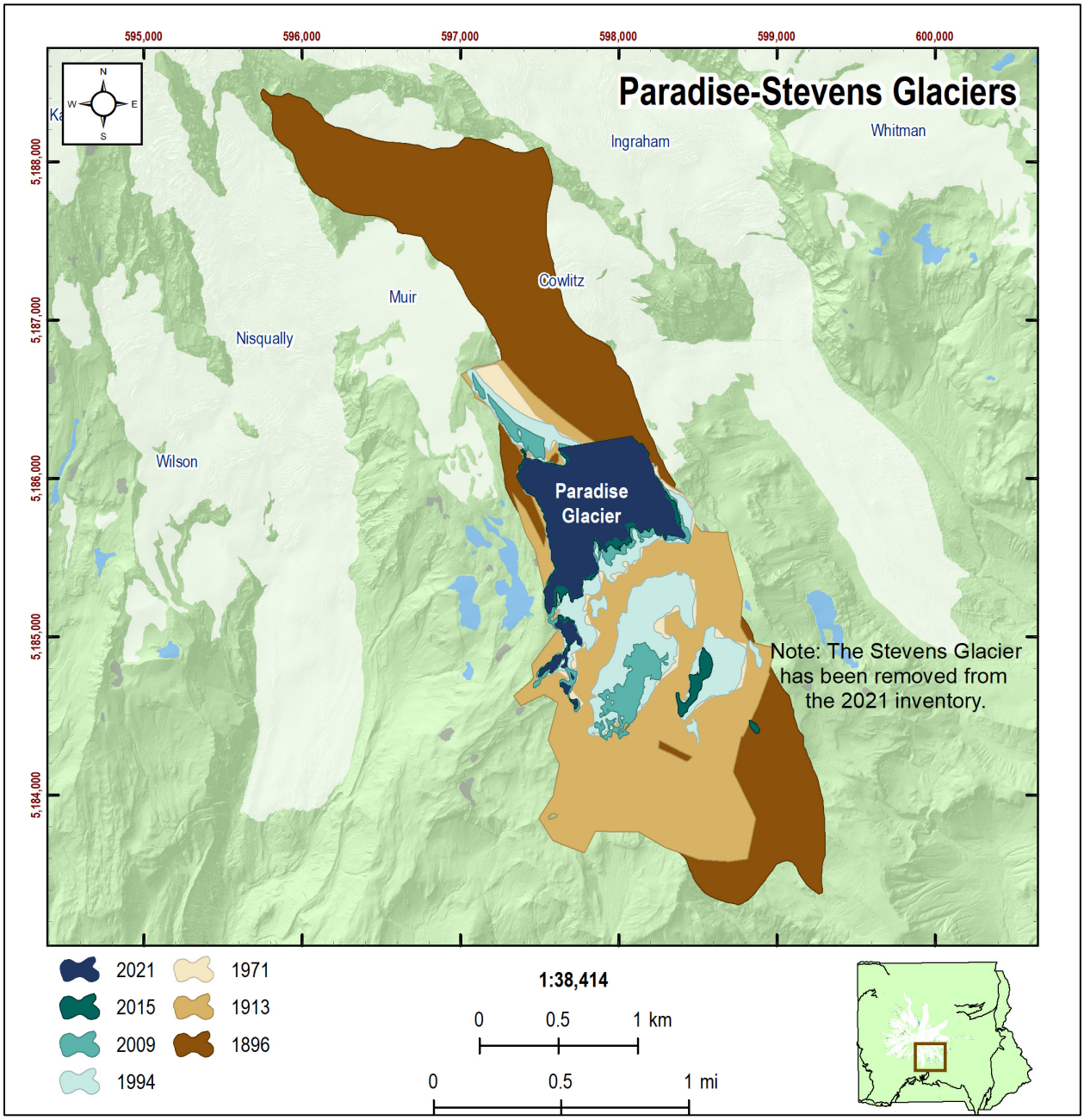


Figure B-15. Detailed map for Paradise-Stevens Glacier over time.

Table B-29. Observed glacial extent and volume for Paradise-Stevens Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	4.863	3.186	1.364	1.338	0.778	0.645	0.581
Extent, mi^2	1.878	1.230	0.526	0.516	0.300	0.249	0.224
Volume, km^3	0.2076	0.1164	0.0365	0.0355	0.0150	0.0124	0.0114
Volume, mi^3	0.0498	0.0279	0.0088	0.0085	0.0036	0.0030	0.0027

Table B-30. Observed change in glacial extent (km^2) for Paradise-Stevens Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	-1.677 (-34.5%)	-3.500 (-72.0%)	-3.526 (-72.5%)	-4.086 (-84.0%)	-4.218 (-86.7%)	-4.283 (-88.1%)
1913	–	-1.823 (-57.2%)	-1.849 (-58.0%)	-2.409 (-75.6%)	-2.541 (-79.8%)	-2.606 (-81.8%)
1971	–	–	-0.026 (-1.9%)	-0.586 (-43.0%)	-0.719 (-52.7%)	-0.783 (-57.4%)
1994	–	–	–	-0.560 (-41.9%)	-0.693 (-51.8%)	-0.757 (-56.6%)
2009	–	–	–	–	-0.133 (-17.1%)	-0.197 (-25.4%)
2015	–	–	–	–	–	-0.064 (-10.0%)

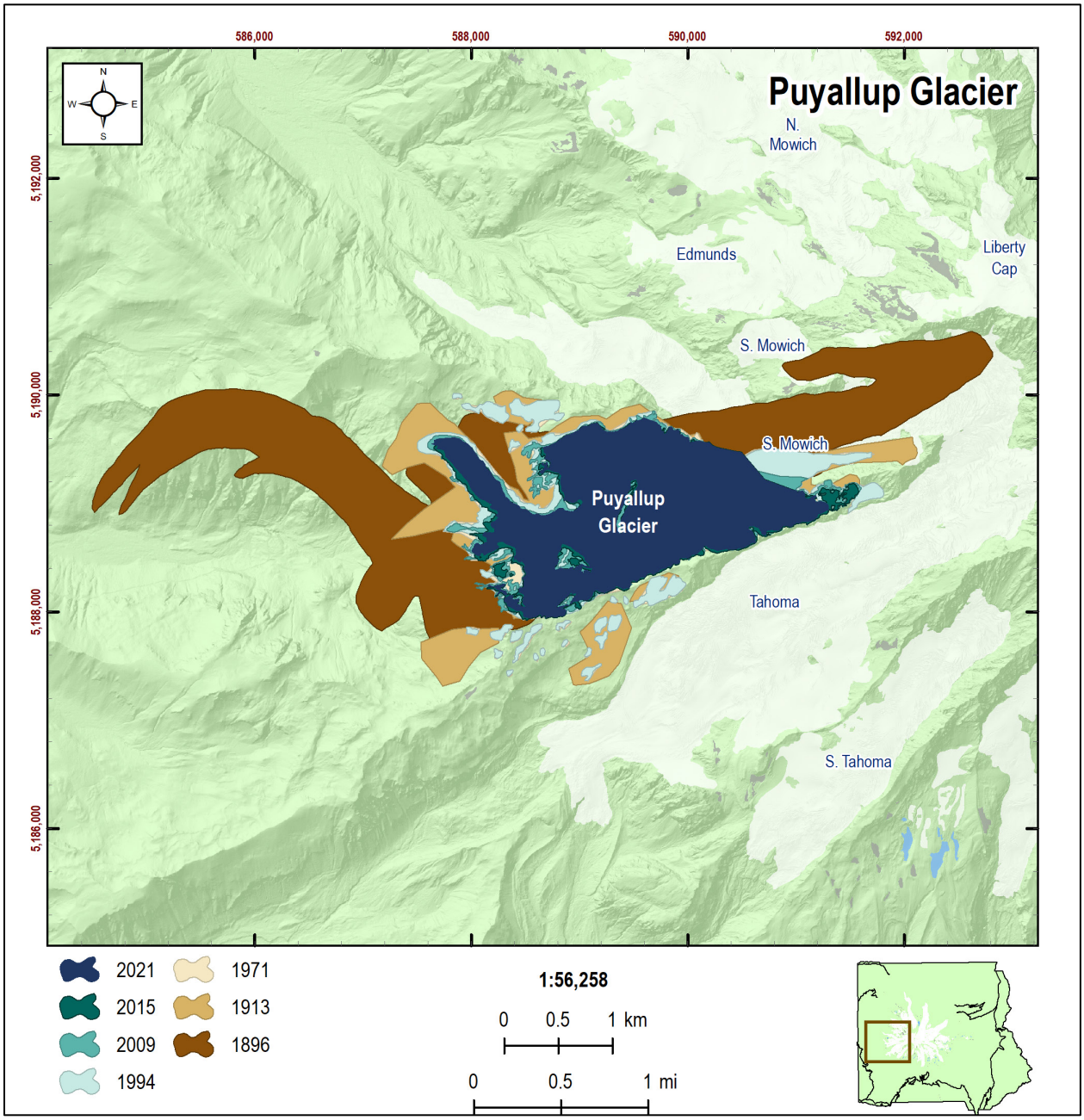


Figure B-16. Detailed map for Puyallup Glacier over time.

Table B-31. Observed glacial extent and volume for Puyallup Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	8.463	5.213	4.316	4.348	3.519	3.258	8.463
Extent, mi^2	3.268	2.013	1.666	1.679	1.359	1.258	3.268
Volume, km^3	0.5233	0.2696	0.2082	0.2104	0.1575	0.1417	0.5233
Volume, mi^3	0.1255	0.0647	0.0500	0.0505	0.0378	0.0340	0.1255

Table B-32. Observed change in glacial extent (km^2) for Puyallup Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	-3.251 (-38.4%)	-4.147 (-49.0%)	-4.115 (-48.6%)	-4.944 (-58.4%)	-5.206 (-61.5%)	-5.366 (-63.4%)
1913	–	-0.897 (-17.2%)	-0.864 (-16.6%)	-1.694 (-32.5%)	-1.955 (-37.5%)	-2.115 (-40.6%)
1971	–	–	+0.032 (+0.7%)	-0.797 (-18.5%)	-1.058 (-24.5%)	-1.218 (-28.2%)
1994	–	–	–	-0.829 (-19.1%)	-1.090 (-25.1%)	-1.251 (-28.8%)
2009	–	–	–	–	-0.261 (-7.4%)	-0.421 (-12.0%)
2015	–	–	–	–	–	-0.160 (-4.9%)

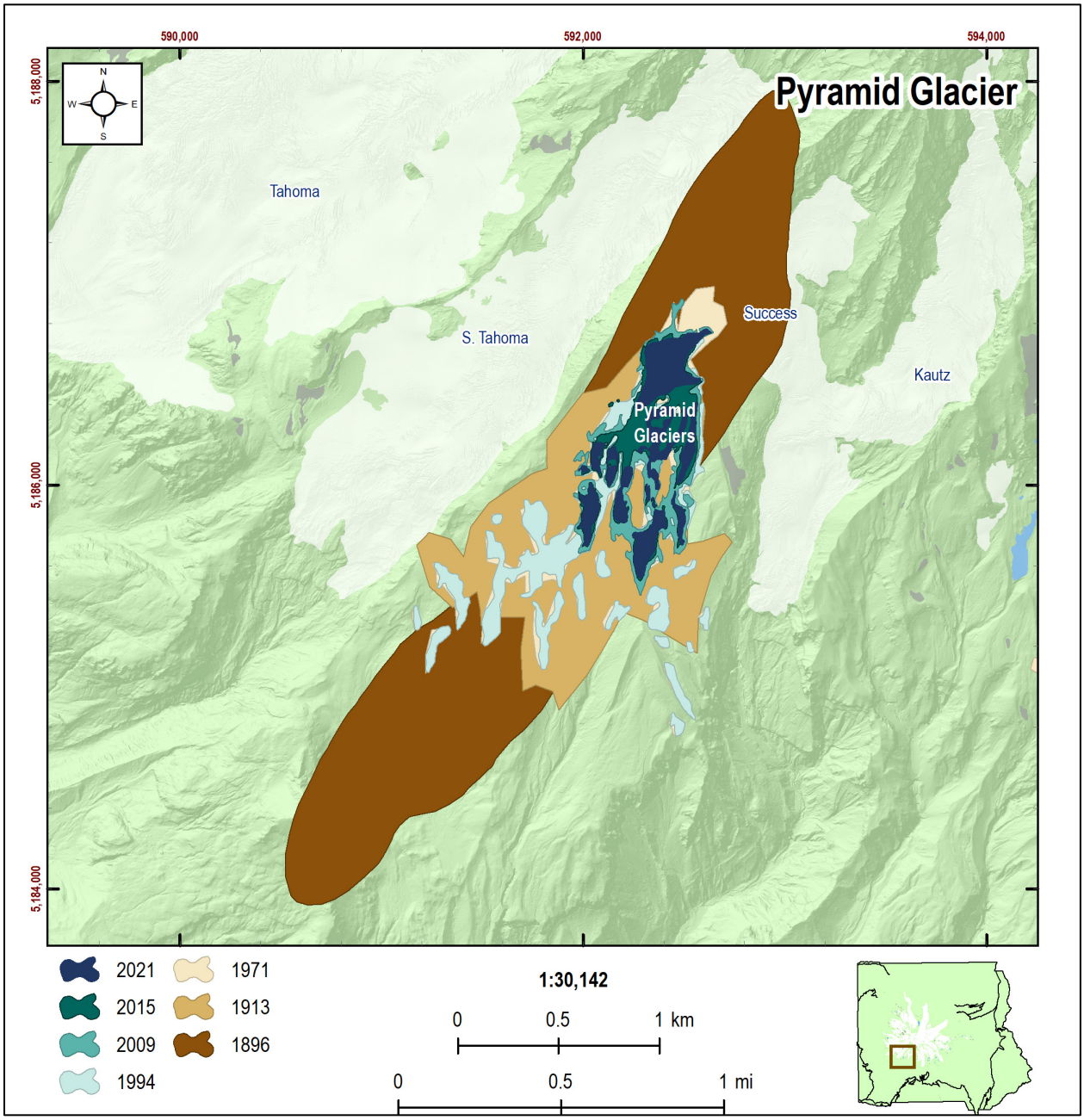


Figure B-17. Detailed map for Pyramid Glaciers over time.

Table B-33. Observed glacial extent and volume for Pyramid Glaciers over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	2.747	1.394	0.710	0.645	0.379	0.262	0.176
Extent, mi^2	1.061	0.538	0.274	0.249	0.146	0.101	0.068
Volume, km^3	0.1036	0.0410	0.0163	0.0143	0.0069	0.0042	0.0024
Volume, mi^3	0.0248	0.0098	0.0039	0.0034	0.0017	0.0010	0.0006

Table B-34. Observed change in glacial extent (km^2) for Pyramid Glaciers over time.

Year	1913	1971	1994	2009	2015	2021
1896	-1.353 (-49.2%)	-2.037 (-74.2%)	-2.102 (-76.5%)	-2.368 (-86.2%)	-2.485 (-90.5%)	-2.571 (-93.6%)
1913	–	-0.685 (-49.1%)	-0.749 (-53.7%)	-1.015 (-72.8%)	-1.132 (-81.2%)	-1.218 (-87.4%)
1971	–	–	-0.065 (-9.1%)	-0.331 (-46.6%)	-0.447 (-63.0%)	-0.533 (-75.2%)
1994	–	–	–	-0.266 (-41.3%)	-0.383 (-59.3%)	-0.469 (-72.7%)
2009	–	–	–	–	-0.116 (-30.7%)	-0.203 (-53.5%)
2015	–	–	–	–	–	-0.086 (-32.9%)

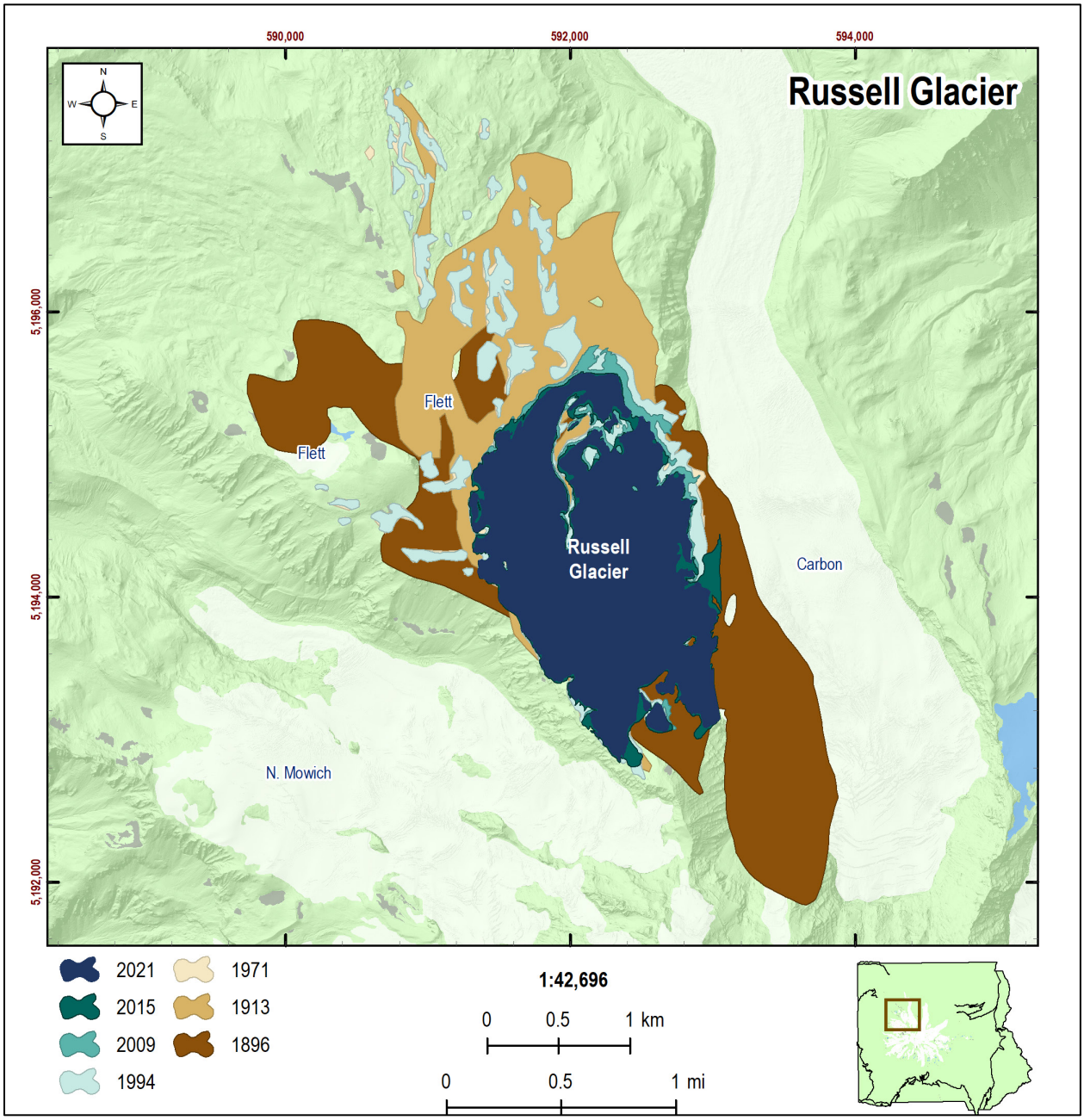


Figure B-18. Detailed map for over time Russell Glacier.

Table B-35. Observed glacial extent and volume for Russell Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	6.605	4.909	3.574	3.637	2.789	2.892	2.706
Extent, mi^2	2.550	1.895	1.380	1.404	1.077	1.117	1.045
Volume, km^3	0.2802	0.1868	0.1211	0.1240	0.0863	0.0907	0.0828
Volume, mi^3	0.0672	0.0448	0.0291	0.0298	0.0207	0.0218	0.0199

Table B-36. Observed change in glacial extent (km^2) for Russell Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	-1.696 (-25.7%)	-3.031 (-45.9%)	-2.968 (-44.9%)	-3.816 (-57.8%)	-3.713 (-56.2%)	-3.900 (-59.0%)
1913	–	-1.335 (-27.2%)	-1.272 (-25.9%)	-2.120 (-43.2%)	-2.017 (-41.1%)	-2.203 (-44.9%)
1971	–	–	+0.063 (+1.8%)	-0.785 (-22.0%)	-0.682 (-19.1%)	-0.868 (-24.3%)
1994	–	–	–	-0.848 (-23.3%)	-0.745 (-20.5%)	-0.931 (-25.6%)
2009	–	–	–	–	+0.103 (+3.7%)	-0.084 (-3.0%)
2015	–	–	–	–	–	-0.187 (-6.5%)

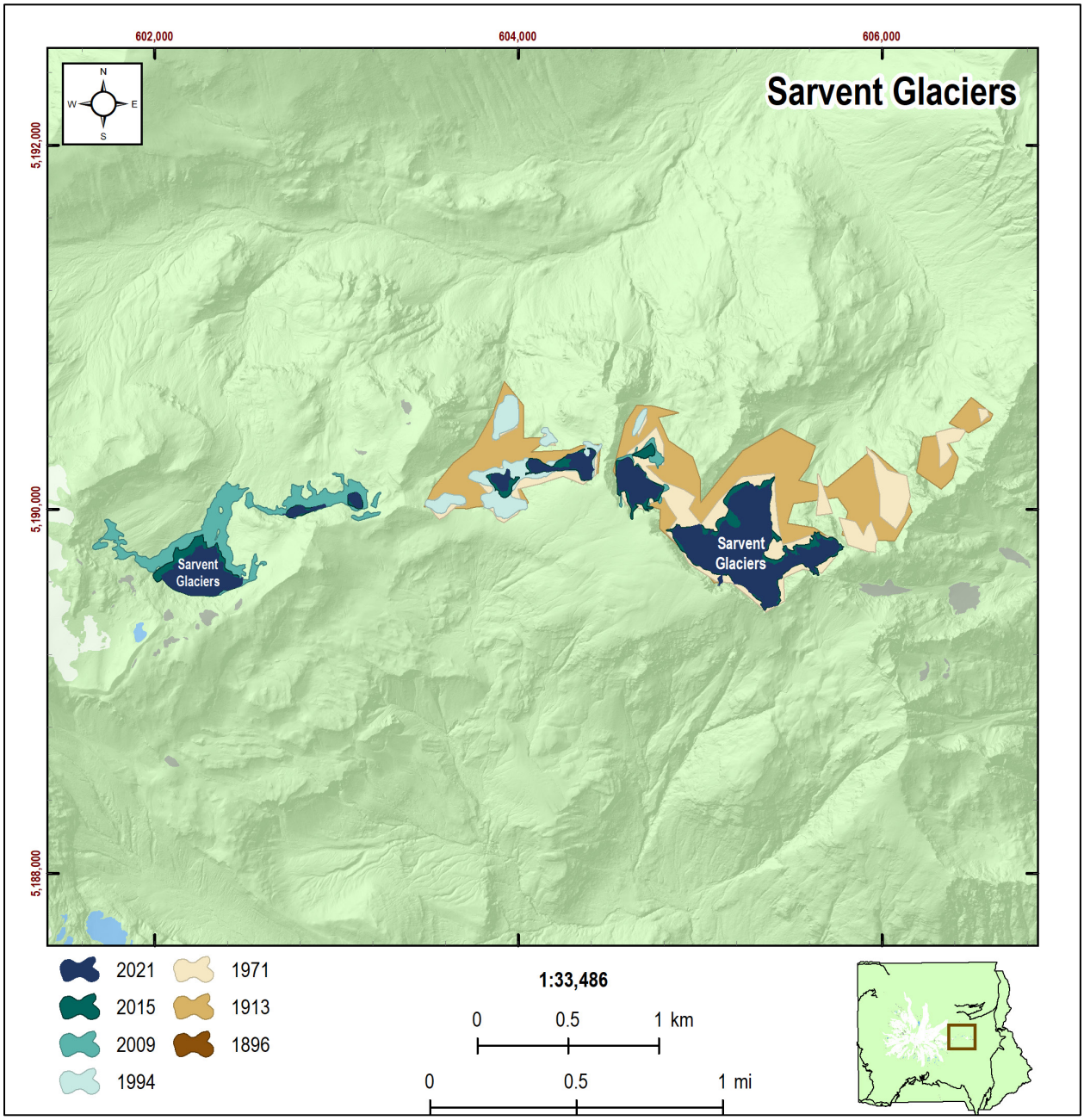


Figure B-19. Detailed map for over time Sarvent Glaciers.

Table B-37. Observed glacial extent and volume for Sarvent Glaciers over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	---	1.148	0.686	0.146	0.695	0.455	0.380
Extent, mi^2	---	0.443	0.265	0.056	0.268	0.176	0.147
Volume, km^3	---	0.0300	0.0148	0.0018	0.0151	0.0085	0.0066
Volume, mi^3	---	0.0072	0.0036	0.0004	0.0036	0.0020	0.0016

Table B-38. Observed change in glacial extent (km^2) for Sarvent Glaciers over time.

Year	1913	1971	1994	2009	2015	2021
1896	–	–	–	–	–	–
1913	–	-0.461 (-40.2%)	-1.002 (-87.3%)	-0.453 (-39.4%)	-0.693 (-60.4%)	-0.767 (-66.8%)
1971	–	–	-0.541 (-78.8%)	+0.009 (+1.3%)	-0.232 (-33.7%)	-0.306 (-44.6%)
1994	–	–	–	+0.549 (+377%)	+0.309 (+212%)	+0.235 (+161%)
2009	–	–	–	–	-0.240 (-34.6%)	-0.314 (-45.3%)
2015	–	–	–	–	–	-0.074 (-16.3%)

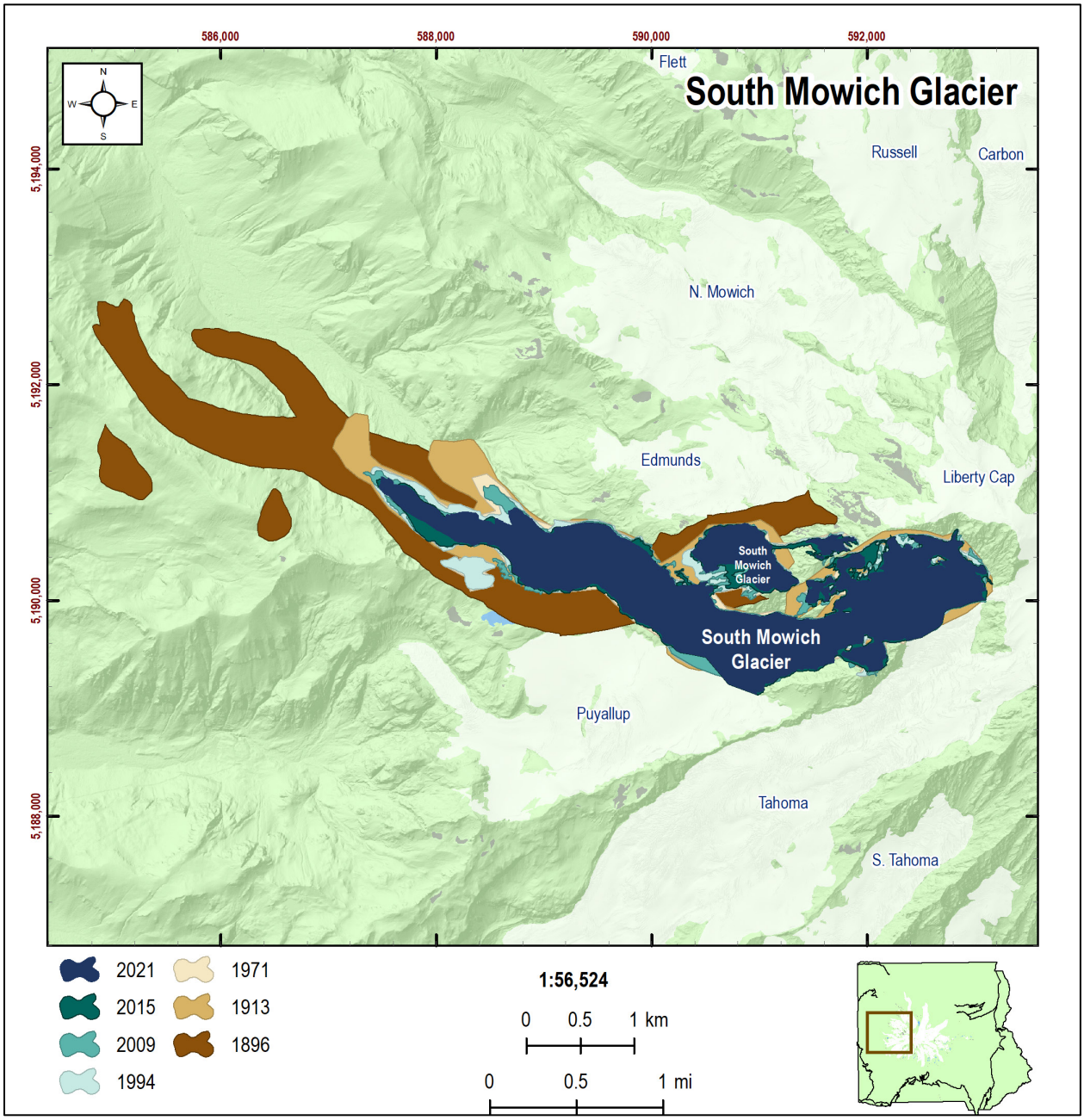


Figure B-20. Detailed map for South Mowich Glacier over time.

Table B-39. Observed glacial extent and volume for South Mowich Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	5.331	4.700	4.091	4.061	3.963	3.766	3.626
Extent, mi^2	2.058	1.815	1.579	1.568	1.530	1.454	1.400
Volume, km^3	0.2348	0.1977	0.1635	0.1619	0.1566	0.1460	0.1387
Volume, mi^3	0.0563	0.0474	0.0392	0.0388	0.0376	0.0350	0.0333

Table B-40. Observed change in glacial extent (km^2) for South Mowich Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	-0.631 (-11.8%)	-1.240 (-23.3%)	-1.270 (-23.8%)	-1.368 (-25.7%)	-1.565 (-29.4%)	-1.705 (-32.0%)
1913	–	-0.609 (-13.0%)	-0.639 (-13.6%)	-0.737 (-15.7%)	-0.934 (-19.9%)	-1.074 (-22.8%)
1971	–	–	-0.030 (-0.7%)	-0.128 (-3.1%)	-0.325 (-8.0%)	-0.465 (-11.4%)
1994	–	–	–	-0.098 (-2.4%)	-0.295 (-7.3%)	-0.434 (-10.7%)
2009	–	–	–	–	-0.197 (-5.0%)	-0.337 (-8.5%)
2015	–	–	–	–	–	-0.139 (-3.7%)

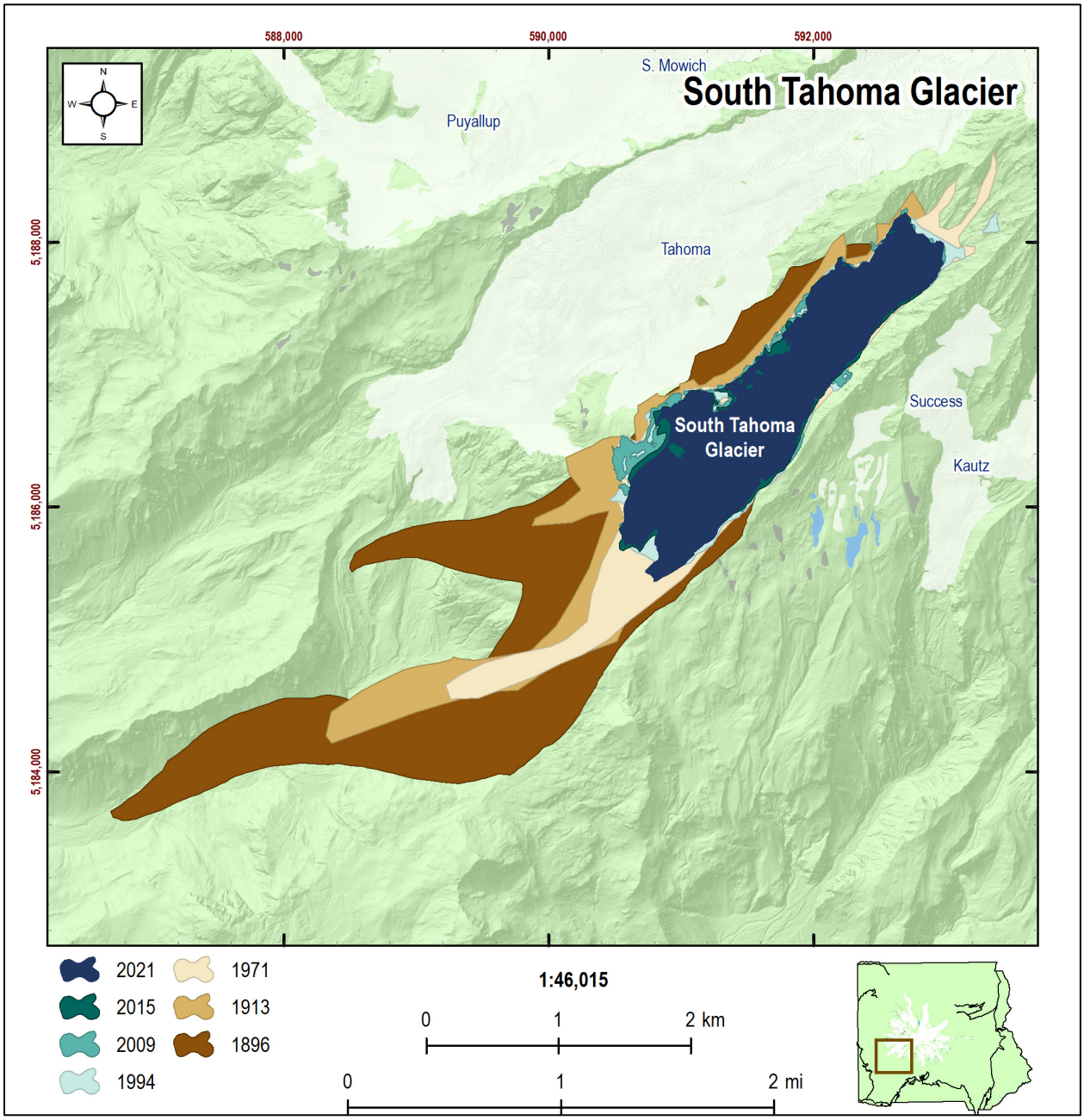


Figure B-21. Detailed map for South Tahoma Glacier over time.

Table B-41. Observed glacial extent and volume for South Tahoma Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	5.926	3.427	2.922	2.233	2.206	2.002	1.947
Extent, mi^2	2.288	1.323	1.128	0.862	0.852	0.773	0.752
Volume, km^3	0.3238	0.1531	0.1230	0.0852	0.0838	0.0733	0.0706
Volume, mi^3	0.0777	0.0367	0.0295	0.0204	0.0201	0.0176	0.0169

Table B-42. Observed change in glacial extent (km^2) for South Tahoma Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	-2.499 (-42.2%)	-3.005 (-50.7%)	-3.694 (-62.3%)	-3.720 (-62.8%)	-3.924 (-66.2%)	-3.979 (-67.1%)
1913	–	-0.506 (-14.8%)	-1.195 (-34.9%)	-1.221 (-35.6%)	-1.425 (-41.6%)	-1.480 (-43.2%)
1971	–	–	-0.689 (-23.6%)	-0.716 (-24.5%)	-0.920 (-31.5%)	-0.975 (-33.4%)
1994	–	–	–	-0.027 (-1.2%)	-0.231 (-10.3%)	-0.286 (-12.8%)
2009	–	–	–	–	-0.204 (-9.3%)	-0.259 (-11.7%)
2015	–	–	–	–	–	-0.055 (-2.7%)

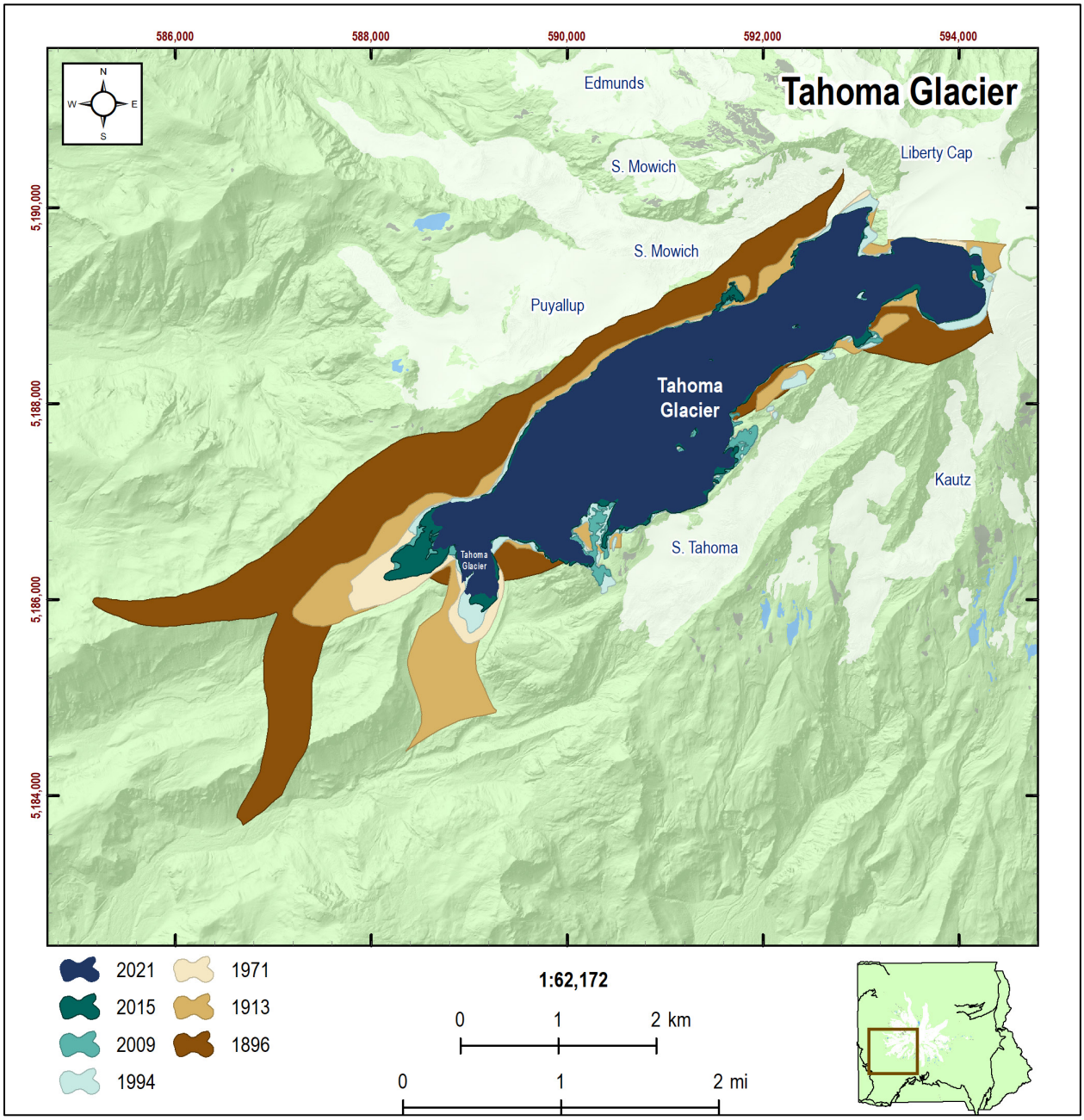


Figure B-22. Detailed map for Tahoma Glacier over time.

Table B-43. Observed glacial extent and volume for Tahoma Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	12.005	9.171	7.619	7.281	6.777	6.787	6.433
Extent, mi^2	4.635	3.541	2.942	2.811	2.617	2.620	2.484
Volume, km^3	0.7333	0.5075	0.3938	0.3701	0.3355	0.3362	0.3125
Volume, mi^3	0.1759	0.1217	0.0945	0.0888	0.0805	0.0807	0.0750

Table B-44. Observed change in glacial extent (km^2) for Tahoma Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	-2.834 (-23.6%)	-4.386 (-36.5%)	-4.724 (-39.4%)	-5.228 (-43.5%)	-5.218 (-43.5%)	-5.572 (-46.4%)
1913	–	-1.552 (-16.9%)	-1.890 (-20.6%)	-2.394 (-26.1%)	-2.384 (-26.0%)	-2.738 (-29.9%)
1971	–	–	-0.338 (-4.4%)	-0.842 (-11.1%)	-0.832 (-10.9%)	-1.186 (-15.6%)
1994	–	–	–	-0.504 (-6.9%)	-0.494 (-6.8%)	-0.848 (-11.6%)
2009	–	–	–	–	+0.010 (+0.2%)	-0.344 (-5.1%)
2015	–	–	–	–	–	-0.354 (-5.2%)

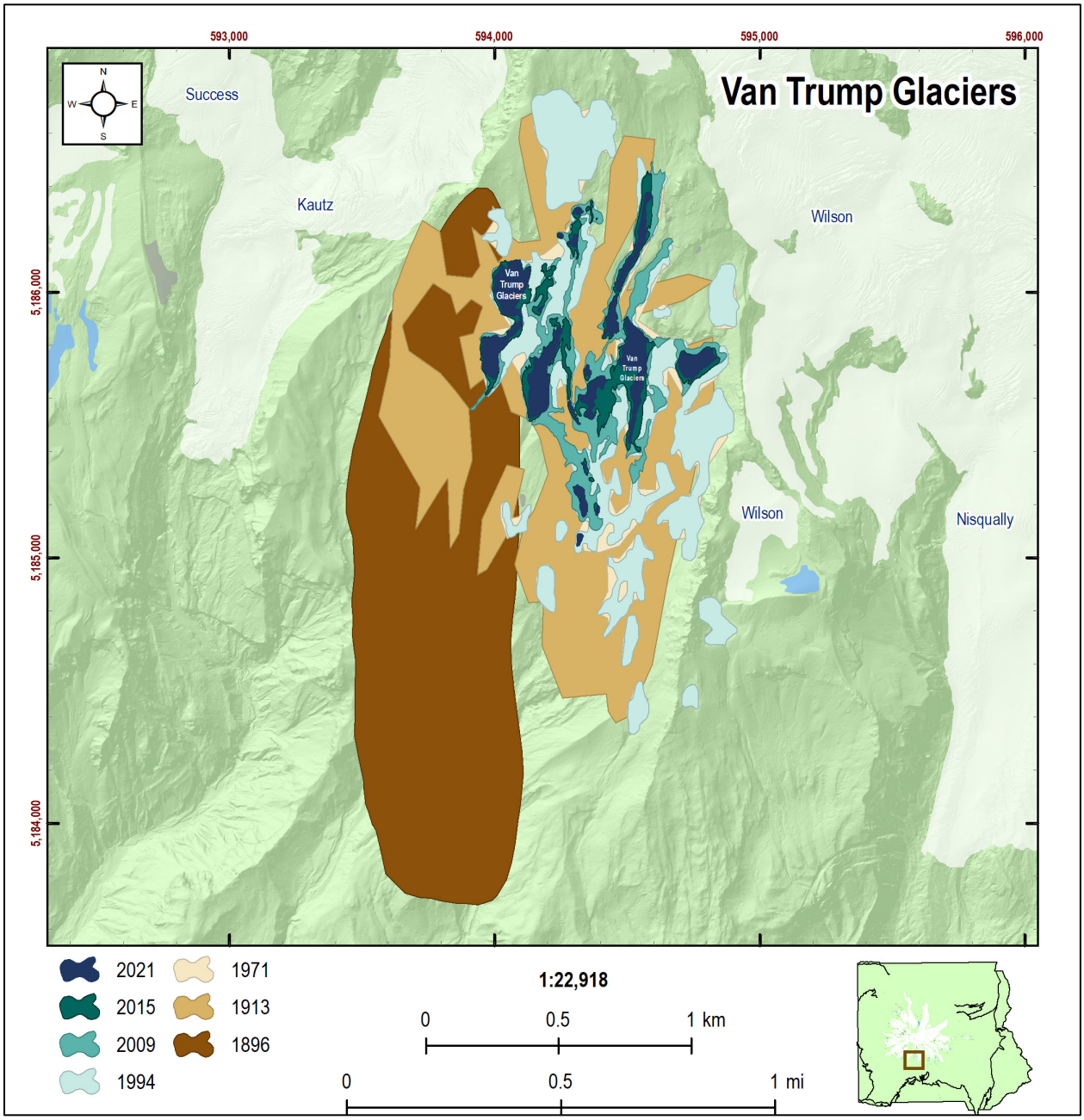


Figure B-23. Detailed map for Van Trump Glaciers over time.

Table B-45. Observed glacial extent and volume for Van Trump Glaciers over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	1.438	1.402	0.681	0.724	0.318	0.176	0.117
Extent, mi^2	0.555	0.541	0.263	0.280	0.123	0.068	0.045
Volume, km^3	0.0433	0.0418	0.0156	0.0169	0.0055	0.0024	0.0014
Volume, mi^3	0.0104	0.0100	0.0037	0.0041	0.0013	0.0006	0.0003

Table B-46. Observed change in glacial extent (km^2) for Van Trump Glaciers over time.

Year	1913	1971	1994	2009	2015	2021
1896	-0.036 (-2.5%)	-0.757 (-52.6%)	-0.714 (-49.6%)	-1.120 (-77.9%)	-1.262 (-87.8%)	-1.321 (-91.9%)
1913	–	-0.721 (-51.4%)	-0.678 (-48.3%)	-1.085 (-77.3%)	-1.226 (-87.5%)	-1.285 (-91.7%)
1971	–	–	+0.043 (+6.3%)	-0.364 (-53.4%)	-0.505 (-74.2%)	-0.564 (-82.8%)
1994	–	–	–	-0.407 (-56.2%)	-0.548 (-75.7%)	-0.607 (-83.9%)
2009	–	–	–	–	-0.142 (-44.6%)	-0.201 (-63.2%)
2015	–	–	–	–	–	-0.059 (-33.6%)

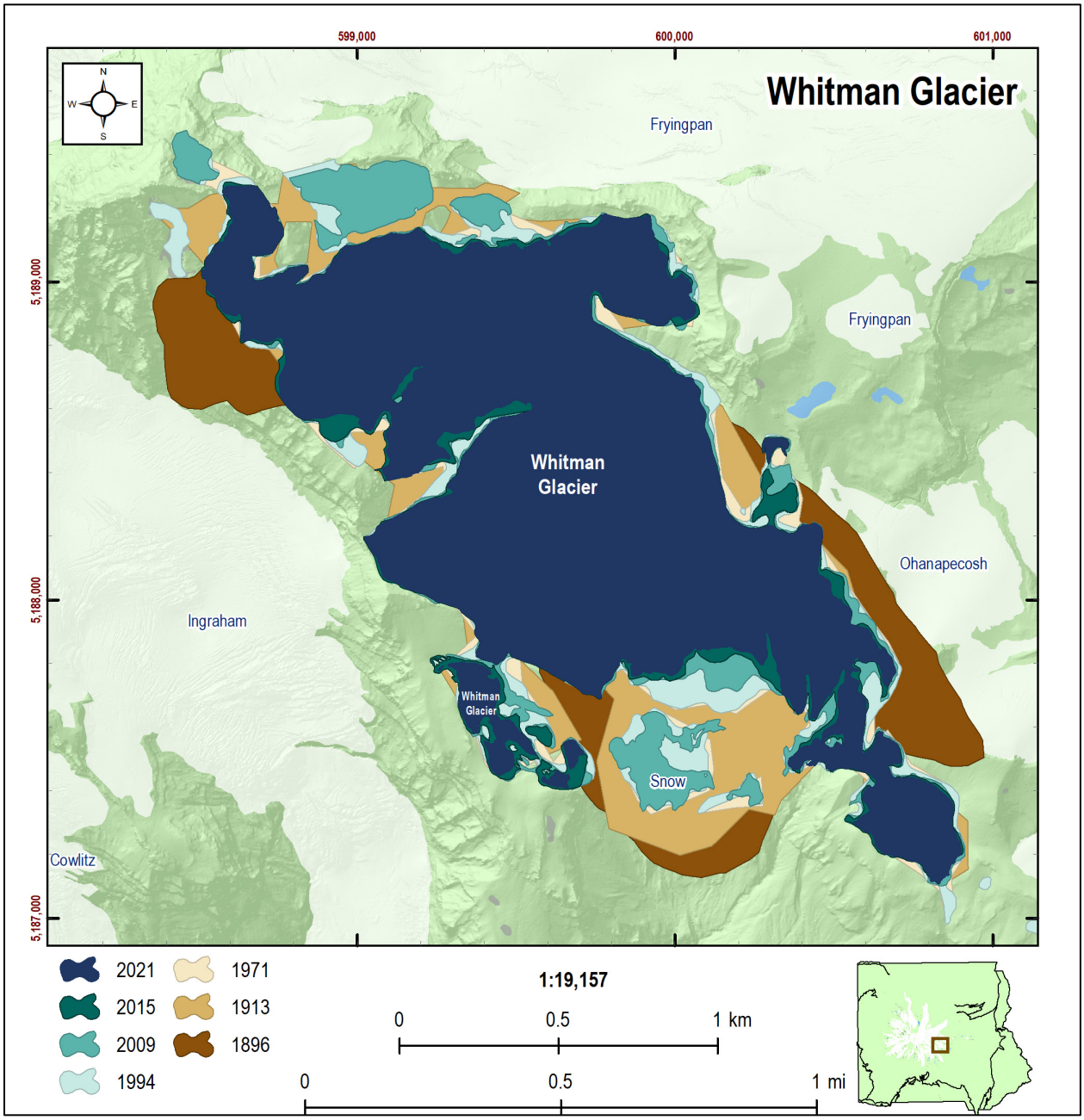


Figure B-24. Detailed map for Whitman Glacier over time.

Table B-47. Observed glacial extent and volume for Whitman Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	1.974	2.432	2.226	2.315	2.101	1.939	1.846
Extent, mi^2	0.762	0.939	0.859	0.894	0.811	0.749	0.713
Volume, km^3	0.0855	0.1137	0.1007	0.1063	0.0931	0.0834	0.0779
Volume, mi^3	0.0205	0.0273	0.0242	0.0255	0.0223	0.0200	0.0187

Table B-48. Observed change in glacial extent (km^2) for Whitman Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	+0.458 (+23.2%)	+0.251 (+12.7%)	+0.341 (+17.3%)	+0.127 (+6.4%)	-0.036 (-1.8%)	-0.129 (-6.5%)
1913	–	-0.207 (-8.5%)	-0.117 (-4.8%)	-0.331 (-13.6%)	-0.493 (-20.3%)	-0.586 (-24.1%)
1971	–	–	+0.089 (+4.0%)	-0.124 (-5.6%)	-0.287 (-12.9%)	-0.380 (-17.1%)
1994	–	–	–	-0.214 (-9.2%)	-0.376 (-16.3%)	-0.469 (-20.3%)
2009	–	–	–	–	-0.163 (-7.7%)	-0.256 (-12.2%)
2015	–	–	–	–	–	-0.093 (-4.8%)

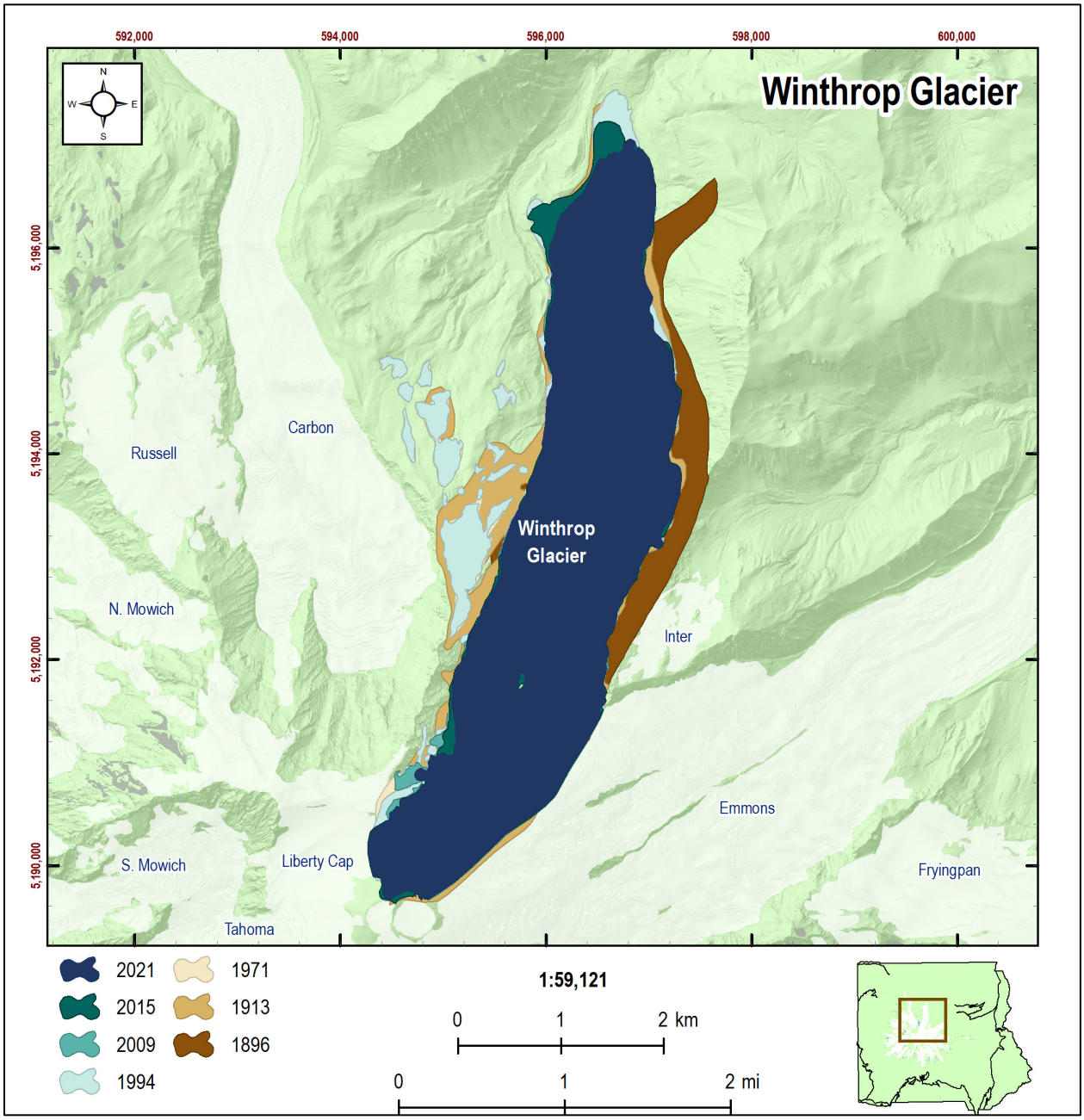


Figure B-25. Detailed map for Winthrop Glacier over time.

Table B-49. Observed glacial extent and volume for Winthrop Glacier over time.

Metric	1896	1913	1971	1994	2009	2015	2021
Extent, km^2	8.235	10.183	9.631	9.943	8.015	8.977	8.688
Extent, mi^2	3.179	3.932	3.719	3.839	3.095	3.466	3.354
Volume, km^3	0.4521	0.6045	0.5601	0.5851	0.4357	0.5087	0.4865
Volume, mi^3	0.1085	0.1450	0.1344	0.1404	0.1045	0.122	0.1167

Table B-50. Observed change in glacial extent (km^2) for Winthrop Glacier over time.

Year	1913	1971	1994	2009	2015	2021
1896	+1.949 (+23.7%)	+1.397 (+17.0%)	+1.709 (+20.8%)	-0.220 (-2.7%)	+0.742 (+9.0%)	+0.453 (+5.5%)
1913	–	-0.552 (-5.4%)	-0.240 (-2.4%)	-2.168 (-21.3%)	-1.207 (-11.8%)	-1.495 (-14.7%)
1971	–	–	+0.312 (+3.2%)	-1.616 (-16.8%)	-0.655 (-6.8%)	-0.943 (-9.8%)
1994	–	–	–	-1.929 (-19.4%)	-0.967 (-9.7%)	-1.255 (-12.6%)
2009	–	–	–	–	+0.962 (+12.0%)	+0.673 (+8.4%)
2015	–	–	–	–	–	-0.289 (-3.2%)

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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