Decline of the globally rare old-growth specklebelly lichen, *Pseudocyphellaria rainierensis*, and its implications for temperate rainforest conservation

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Abstract

Epiphytic lichens are key components of temperate rainforests, where they contribute to forest hydrology, nutrient cycles, food webs, and overall biomass and biodiversity. Despite their ecological importance and sensitivity to environmental change few protections exist for lichen conservation and management. *Pseudocyphellaria rainierensis*, or old-growth specklebelly lichen, is considered an important indicator of high conservation value, temperate rainforest in the Pacific Northwest bioregion of North America. Concerns about continued habitat destruction and recent population losses due to wildfires prompted us to investigate the status of *P. rainierensis.* We gathered all known historical records of the species and conducted an extensive population assessment in Washington state. We revisited 31 of the 143 historical sites (22%) and did not recover *P. rainierensis* at 13 sites, indicating that populations declined by 41%. Our analysis of Forest Inventory and Analysis (FIA) data revealed the presence of *P. rainierensis* in eight of 664 forest plots surveyed over a 20-year period. During field surveys we discovered four new sites and a review of records from the community science database, iNaturalist, identified eight new sites. Our findings underscore the critical need to regularly monitor old-growth dependent lichen populations and plan for strategic surveys to identify potential new locations where these species may occur. Our study offers a model for successful monitoring of rare species through public-private partnerships and engagement with community science efforts. Using these methods, forest managers and policy makers can utilize the best available scientific information for making conservation decisions.

Keywords: *Lichens; fungi; rare species; conservation; old-growth forests; phytogeography*

1. Introduction

Temperate rainforests are one of the rarest ecosystems on earth, covering just 2.5% of global forest area (DellaSala 2011; Silver et al. 2024). While temperate rainforests can be found across the globe in Chile and Argentina, Japan, Australia, Tasmania and New Zealand, as well as the United Kingdom and Norway, by far the most expansive stretch exists along the Pacific Northwest coast of North America between northern California and southeast Alaska (DellaSala 2011). When these forests reach maturity, they boast one of the highest levels of ecosystem productivity and carbon storage of any forest type on earth (Keith et al. 2009; Smithwick et al. 2002; Woodbury et al. 2007). Unfortunately, only a tiny fraction of the historical area of old-growth temperate rainforest remains. For example, due to aggressive logging practices in British Columbia, Canada, only 1-2% of high productivity, low elevation coastal temperate rainforest remnants persist today (Price et al. 2021). The loss of these old-growth forests has led to negative consequences for biodiversity, carbon sequestration and ecosystem function (Pan et al. 2024; Smithwick et al. 2002). These negative impacts extend beyond loss of ecosystem services to the destruction of human connection with these landscapes through recreation, spiritual and cultural practices (Case et al. 2020; Gilhen-Baker et al. 2022).

In the United States, concerns about the detrimental impacts of logging on old-growth dependent species contributed to the development of the "Survey and Manage" Program of the Northwest Forest Plan (NWFP; USDA & USDI 1994b). This plan aims to protect rare species associated with late-successional (80-200 years old) and old-growth forests (>200 years old) on federal lands. Approximately 400 species were originally listed under this program leading to increased search efforts and understanding of the range and relative threats to rare and old-growth associated species. However, the implementation of the plan created conflicts, particularly with meeting timber harvest management objectives. These conflicts, along with the large scale of implementation (~9.7 million areas of federal forest lands) and lack of funds eventually led to an amendment to the program guidelines to streamline the management and implementation process (Molina et al. 2006; USDA Forest Service & BLM 2001). Today the updated "Survey and Manage" guidelines continue to be implemented in Forest Regions 5 & 6 where they aim to protect hundreds of rare species. In 2024, a new federal advisory committee formed to revise the Northwest Forest Plan (US Forest Service 2024). The protection of the majority of mature and old-growth temperate rainforests in the United States now lies at a crossroads; the update to this plan could position the United States with greater protections for the last remaining old-growth temperate rainforests, enhanced carbon storage and increased climate resilience (Halsey 2024). Or it could pave the way for loosening restrictions on mature and old-growth timber harvesting and potentially reduce or eliminate monitoring of rare species through “Survey and Manage” efforts.

Epiphytic lichens are key components of temperate rainforests worldwide, where they contribute to forest canopy and understory hydrological regimes, nutrient cycles, food webs, and overall biomass and biodiversity (Ellis 2012). These species are often sensitive to disturbance such as forest fire and logging (Johansson 2008, Miller et al. 2018; Rose 1976) and many are dispersal-limited (Goward 2003; Sillett et al. 2001). Despite their ecological importance and sensitivity to environmental change few protections exist for the conservation and management of forest epiphyte lichens at the federal level in the United States (Allen et al. 2019). For example, only two out of approximately 5,823 lichen species that occur in North America north of Mexico are protected by the Endangered Species Act (Esslinger 2021; USFWS 2007, 2013). At the state-level, Natural Heritage Programs compile and maintain lists of rare and endangered lichen species (Groves et al. 1995). However, there is no formal process or funding to support adding new species to the state’s lists. Instead, the process relies mainly on volunteer work of regional lichen experts to revise and update rare species lists.

Pseudocyphellaria rainierensis Imsh. (old-growth specklebelly lichen) is a rare, epiphytic macrolichen endemic to the Pacific Northwest coast of North America from Alaska to Oregon (Glavich 2013). This iconic species, much like the northern spotted owl, is considered an important indicator of high conservation value, ancient temperate rainforest (Sillett and Goward 1998; Miller et al. 2020). Henry Imshaug described the species from specimens collected along the Ohanapecosh River within the boundaries of Mount Rainier National Park in Washington state (Imshaug 1950). Since its discovery, *P. rainierensis* has been documented in late-seral and old-growth forest stands in the western Cascades and coast range of Oregon, the western Cascades and Olympic Peninsula of Washington, the coastal western hemlock zone and Vancouver Island of British Columbia, and the coastal temperate rainforest of southeastern Alaska (Rosso et al. 2000; Sillett and Goward, 1998). According to NatureServe (2017), the global status of *P. rainierensis* is apparently secure (G4) with the following state-level rankings: vulnerable (S3) in Oregon and Washington, and imperiled to vulnerable (S2-S3) in Alaska (ANHP 2024; WNHP, 2024). In Canada, *P. rainierensis* holds the national rank of N2/N3 and the provincial rank of imperiled to vulnerable (S2/S3) in British Columbia (Environment Canada 2016). The species was given special concern status under the Canadian Species at Risk Act (SARA) in 2012 and by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2010.

There are numerous clear threats to *Pseudocyphellaria rainierensis*. Increases in the frequency and severity of forest fires have accelerated the loss of remaining habitat for this species. For example, The Beachie Creek Fire in the Willamette National Forest burned 193,572 acres from August to November 2020, devastating the last remaining watershed of low-elevation, old-growth forests in Oregon and destroying one of the largest known populations of *P. rainierensis* (Villella et al. 2023). Concerns that continued land use changes and habitat destruction are leading to population declines of *P. rainierensis* prompted us to investigate its current status in Washington state.

The overarching goal of this research was to assess the condition of temperate rainforest old-growth associated epiphytes by comprehensively documenting the status of the flagship species, *Pseudocyphellaria rainierensis,* in Washington state. We specifically aimed to answer the following questions: 1) Are *Pseudocyphellaria rainierensis* populations declining in Washington state? 2) Where are populations thriving and where do we see the greatest declines? 3) What measures are needed to conserve and protect remaining populations? To address these questions, we gathered all available historical records of the species and completed extensive site revisits to document species abundance and habitat characteristics for each population. Based on these findings we provide an updated assessment of sites in Washington that are currently functioning as refugia for populations of *Pseudocyphellaria rainierensis*, as well as those habitats that no longer support viable lichen populations. We also present recommendations for forest managers to conserve this species and promote forest stand characteristics that would support old-growth epiphyte community viability in the future.

2. Materials and Methods

2.1 Study Species

Pseudocyphellaria rainierensis is endemic to the Pacific Northwest coast of North America from Alaska to Oregon. Henry Imshaug described the species from specimens collected along the Ohanapecosh River within the boundaries of Mount Rainier National Park in Washington state (Imshaug1950). Since its discovery, *P. rainierensis* has been documented in late-seral and old-growth forest stands in the western Cascades and coast range of Oregon, the western Cascades and Olympic Peninsula of Washington, the coastal western hemlock zone and Vancouver Island of British Columbia, and the coastal temperate rainforest of southeastern Alaska (Glavich 2013; Sillett and

Goward 1998). Within forest stands, the distribution of *Pseudocyphellaria rainierensis* has been described as "patchy", possibly due to poor dispersal abilities and/or reliance on nutrient enrichment.

Pseudocyphellaria rainierensis is characterized by a blue-green to blue-gray upper surface, a white to tan tomentose lower surface speckled with pseudocyphellae, and the presence of sparse to abundant lobules and isidia (Imshaug 1950; McCune and Geiser 2023). The species has rarely been observed to produce apothecia (Sillett and Goward 1998). As a tripartite species, *P. rainierensis* possesses a primary green algal photobiont, forming a continuous layer throughout the thallus, and a primary cyanobacterial photobiont, sequestered in scattered cephalodia that appear as warts on the upper and lower surface of the thallus (Sillett and Goward 1998). This species contributes to forest food webs and nutrient cycles via the nitrogen-fixing capabilities of the cyanobacterial photobiont (Millbank 1978; Sillett and Goward 1998).

2.2 Historical Records

To assess the current status of *Pseudocyphellaria rainierensis* populations in Washington state, we searched and compiled records for occurrences and collections of the species in Washington state. Occurrences were defined according to NatureServe criteria, where a 1 km separation distance is used to determine the minimum distance between populations (NatureServe 2002). Our search yielded 186 records from the Consortium of Lichen Herbaria (CLH), 36 records from Olympic and North Cascades National Park Service (NPS) herbaria, 45 records from the United States Forest Service (USFS) National Threatened Endangered Sensitive Species (TES) Program and 43 records obtained through internal (23) and external queries (20) of the USFS Forest Inventory and Analysis (FIA) database. All 222 herbarium records from the CLH and NPS were cleaned using OpenRefine v3.7.6. Records without coordinates were georeferenced using the GEOLocate Web Application. We used the *distinct* function from the R package 'dplyr' (v1.0.10) to retain unique record identification numbers and coordinates (decimal latitude/longitude) within each source dataset. Both sets of herbarium and FIA records were combined using the *bind_rows* function from the 'dplyr' package. All datasets were then merged using the *reduce* function in the R package 'purrr' (v.1.0.4) with the full join option. We then spatially thinned the merged dataset to a 1 km resolution using the *thin* function from the R package 'spThin' (v0.2.0). This workflow was performed using R v.4.4.0 (R Core Team 2024). Thinned data was plotted in ArcGIS Pro v3.3.0. Our final dataset represents the total number of unique occurrences (sites) of *P. rainierensis* in Washington for all available records.

To supplement herbarium records and gain a more detailed understanding of *Pseudocyphellaria rainierensis* rarity in Washington, we examined lichen occurrence data from the USFS FIA program (Westfall et al. 2022). The FIA program supports a national network of randomly selected permanent plots across all forested lands in the United States that are re-surveyed every 5-10 years to assess forest health over time. Our initial FIA dataset included all available plots for Region 6 (Washington and Oregon), totaling 3,914 records spanning 1993 to 2012. All duplicate plot numbers and records from Oregon were filtered from the dataset using the *filter* function in the 'dyplr' R package. The remaining records for Washington were plotted in ArcGIS and geoprocessed using the analysis tool *clip* to extract all records within our study area. All remaining records were spatially joined with our *P. rainierensis* dataset to identify FIA plots revisited during our surveys.

We searched the community science database iNaturalist (2024) for *Pseudocyphellaria rainierensis* records within Washington state. First, we confirmed the correct identification for each of the *P. rainierensis* photographic observations. Then we downloaded these data directly from iNaturalist using Washington as a geographic filter and "*Pseudocyphellaria rainierensis*" as a taxon filter, providing 21 records for observations made from 2021 to 2024. The precise geographic locations of vulnerable species are obscured in iNaturalist to protect the location of these taxa. So we created an iNaturalist project to document and track occurrence records for *Pseudocyphellaria rainierensis* across Oregon and Washington (Calabria and Sharrett 2024). Individual observers then shared unobscured coordinates with the project. To identify iNaturalist records representing new *P. rainierensis* occurrence locations, records associated with this research were manually removed, and the remaining records were merged with our processed dataset containing unique sites from the CLH, NPS, TES, and FIA and applied the *thin* function retaining only iNaturalist records representing unique sites. Our results were plotted using ArcGIS Pro.

2.3 Field Surveys

Following our review of herbarium records, we revisit 31 known sites from June 2021 to September 2022, aiming to cover a broad geographic range of sites. We conducted intuitive controlled surveys during revisits for a minimum of 30 minutes and a maximum of 2 hours (Derr et al. 2003a, 2003b; Ministry of Environment and Climate Change Strategy Ecosystems Branch 2018;). We classified the abundance of the species at each site according to protocols used by the USFS Pacific Northwest Region Air Resource Management Program (Geiser 2004). Those protocols employ a rating system using the following values: 1 - *Rare* (< 3 individuals); 2 - *Uncommon* (4-10 individuals); 3 - *Common* (10-40 individuals), and 4 - *Abundant* (occupying > 50% of the available substrate). Each phorophyte within the search area was treated as a functional individual (Yahr et al. 2024). We also conducted opportunistic searches in route to historical site revisits or when target habitats were encountered during field work. We documented abundance and habitat characteristics for these new occurrences when *P. rainierensis* was found. We collected one voucher specimen from each site we visited and deposited them in the Evergreen State College herbarium (EVE; Supplement 1).

To characterize the habitat for the species, we recorded host tree species, stand age, percent canopy cover, distance to streams or rivers, maximum and minimum elevation, and a co-occurring species list for each confirmed population of *Pseudocyphellaria rainierensis* (Table 1, Appendix 1 & 2). Vascular plants species nomenclature follows (Hitchcock and Cronquist 2018), for non-vascular species (Flora of North America, 1993) and for lichen species Esslinger (2021) and McCune and Geiser (2023). Stand age was estimated using USFS Pacific Northwest Region Air Resource Management Program protocols and the characters described in Powell, 2012 (See Table 1; Geiser 2004). Stand age estimates use the following four categories: Early Seral (grasses and forbs, shrubs and seedlings, pole saplings; 1-40 years; 0-1 canopy layers); Mid-Seral (young trees; 40-80 years; 2 canopy layers); Late-Seral (mature trees; < 140 years; 3+ canopy layers), and Old Growth/Climax Community (>140 years old; 3+ canopy layers). Values for distance to streams or rivers and canopy cover were obtained using ArcGIS Pro. The *near* analysis tool was used to estimate the distance of recorded point locations from the National Hydrography Database Plus version 2.1 flowlines layer (U.S. Environmental Protection Agency 2023). The spatial analysis tool *extract values to points* was used to extract values for canopy cover from the National Land Cover Database (NLCD) 2021 USFS Tree Canopy Cover CONUS (continental United States) layer (Dewitz 2021). Elevation data was recorded in the field using iPhone 11 and verified using the CalTopo (CalTopo LLC 2021). All photographs were taken in situ with the iPhone 11 and Canon TG-4. Maps were created in ArcGIS Pro and figures were prepared in Inkscape v1.2.2 (Inkscape Developer 2022).

Table 1 Summary of site characteristics for *Pseudocyphellaria rainierensis*. Weather data was obtained from WorldClim (Fick & Hijmans, 2017) Stand age and abundance ratings were assessed according to protocols established by the US Forest Service (Geiser, 2004). Distance to streams was calculated using ArcGIS Pro. An asterisk symbol (*) denotes the type locality for the species. A cross (†) indicates new sites. A double cross (‡) indicates historic sites. Abundance scores are ranked as follows: 1 = Rare (≤ 3 individuals), 2 = Uncommon (4-10 individuals), 3 = Common (10 - 40 individuals), 4 = Abundant (Occupying ≥ 50 percent of all available substrate)

Locality	Region	Abundance	Host Tree Species	Stand Age	Dist. to Stream (m)	Percent Canopy Cover	Annual Mean Temp. (°C)	Annual Precipitation (mm)	Precip. Wettest Month (mm)	Precip. Driest Month (mm)	Ave. Elevation (m)
Panther Creek*‡	Mount Rainier	2	*Tsuga heterophylla, Alnus rubra*	Late-seral	12	55	7.3	1446	230	29	693
Tahoma Creek‡	Mount Rainier	3	*A. rubra, Thuja plicata*	Mid-/Late-seral	52	75	7.5	2056	316	45	740
Barclay Lake	North Cascades	2	*T. heterophylla, Abies amabilis*	Old-growth/ Climax cmty.	20	78	6.6	2243	355	43	704
Deception Creek	North Cascades	3	*T. heterophylla*	Old-growth/ Climax cmty.	125	73	6.0	1825	314	30	740
Deer Falls	North Cascades	3	*T. heterophylla*	Old-growth/ Climax cmty.	36	84	7.1	1913	311	35	577
Dingford Creek	North Cascades	3	*A. amabilis*	Late-seral/Old - growth	71	81	6.0	2196	353	40	755
Elliot Creek	North Cascades	3	*T. heterophylla, A. amabilis*	Late-seral	135	83	5.6	2114	338	42	774
Huckleberry Creek	North Cascades	2	*Acer circinatum*	Mid-/Late-seral	65	72	7.3	1781	274	39	722
North Fork Sauk River†	North Cascades	3	*T. heterophylla, A. amabilis*	Old-growth/Climax cmty.	61	80	6.1	1923	318	36	732
South Fork Cascade River	North Cascades	3	*T. heterophylla*	Late-seral	8	75	6.8	1614	265	34	554
Seven Lakes Creek	Olympic Peninsula	3	*T. heterophylla, A. amabilis*	Late-seral	78	81	6.2	2561	419	50	682

Chikamin Creek†	Olympic Peninsula	1	*T. heterophylla*	Old-growth/ Climax cmty.	5	80	6.5	2834	453	55	759
Colonel Bob	Olympic Peninsula	3	*T. heterophylla, A. amabilis*	Old-growth/ Climax cmty.	78	82	7.4	3002	483	58	630
Hoh Creek	Olympic Peninsula	2	*A. rubra*	Old-growth/ Climax cmty.	10	73	7.7	2418	399	46	309
Pete's Creek	Olympic Peninsula	3	*T. heterophylla*	Old-growth/ Climax cmty.	4	80	8.0	2979	481	57	488
South Fork Skokomish	Olympic Peninsula	3	*T. heterophylla*	Old-growth/ Climax cmty.	130	77	7.8	2476	405	47	486
Staircase†	Olympic Peninsula	2	*T. heterophylla*	Old-growth/ Climax cmty.	34	79	8.2	2063	346	38	272
Success Creek†	Olympic Peninsula	2	*T. heteorphylla, A rubra*	Late-seral	117	75	6.7	2589	424	49	576
Big Creek	South Cascades	1	*T. heterophylla*	Old-growth/ Climax cmty.	58	79	8.2	2001	332	28	601
Cedar Flats	South Cascades	3	*T. heterophylla, A. amabilis, A. circinatum, Taxus brevifolia*	Old-growth/ Climax cmty.	1095	81	8.9	2227	366	31	436
Paradise Creek	South Cascades	3	*A. circinatum, A rubra, T. heterophylla*	Climax cmty./Late Seral	34	76	8.3	2052	341	26	477
Quartz Creek	South Cascades	3	*T. heterophylla, T. plicata, A. rubra*	Old-growth/ Climax cmty.	2	78	8.1	1843	306	26	539

3. Results

3.1 *Pseudocyphellaria rainierensis* has been lost from 41% of surveyed sites in Washington State

Data cleaning of 310 available records for *Pseudocyphellaria rainierensis* resulted in 143 unique sites for the species in Washington state recorded between 1948 and 2016. We revisited 31 of the 143 sites (22%) and successfully recovered *P. rainierensis* at 18 sites. With regards to abundance, *P. rainierensis* was common at 13 sites (72%), uncommon at four sites (22%), and rare at one site (5.5%). We did not recover *P. rainierensis* at 13 of the sites we surveyed which equates to a 41% decline observed at sites we revisited and overall 9% decline based on all available records for the species (Figure 1A; Table 1). Of the 143 total records, 18 are considered historical by NatureServe's definition, meaning these sites have not been resurveyed in more than 40 years (Hammerson et al. 2020). Of the 18 sites that we successfully relocated *P. rainierensis* in our survey, two are considered historical. Of the 13 sites that did not recover *P. rainierensis*, 4 are considered historical. A selection of photographs of the species at sites where it was recovered are presented in Figure 2.

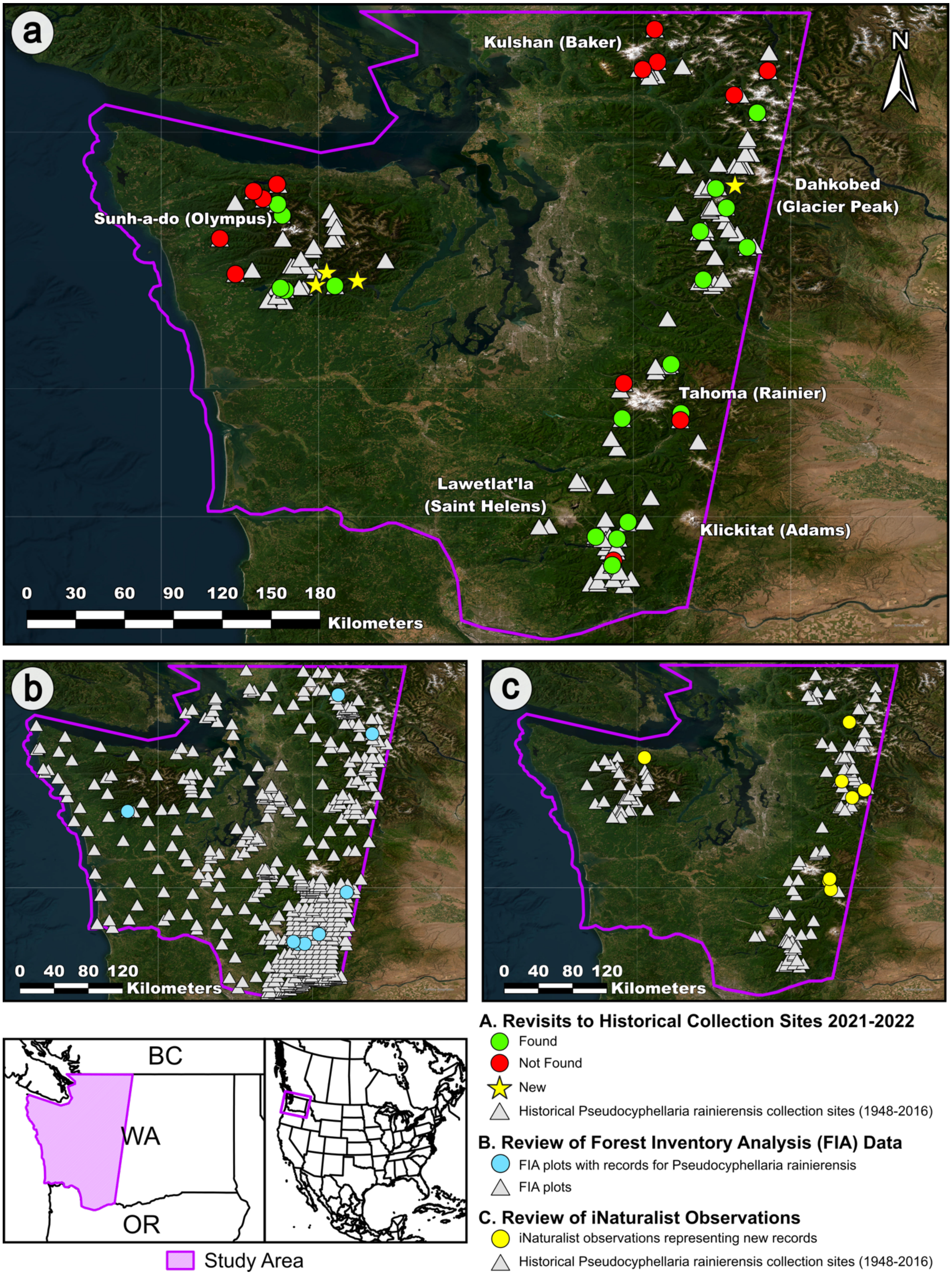
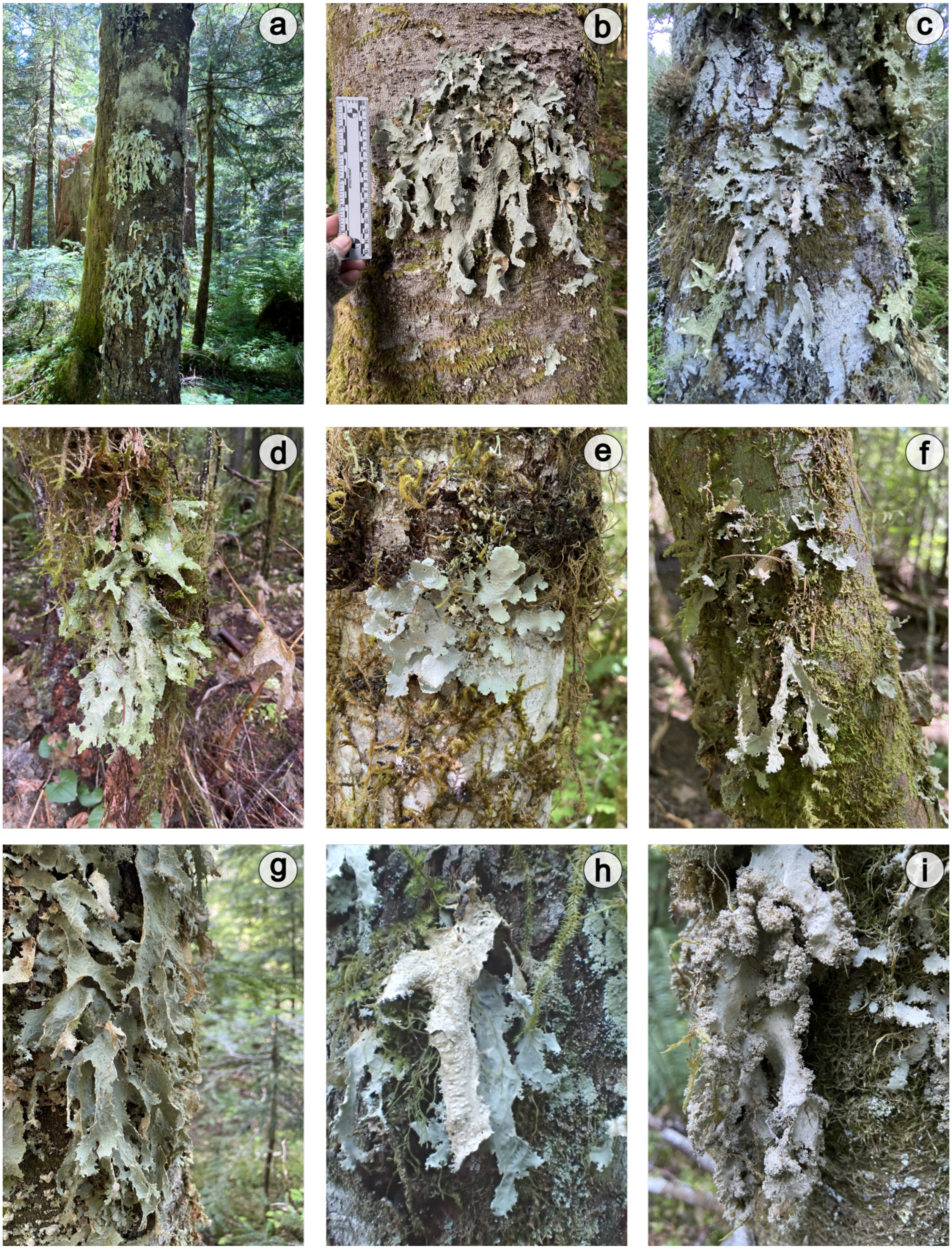

a
Kulshan (Baker)
Dahkobed
(Glacier Peak)
Sunh-a-do (Olympus)
Tahoma (Rainier)
Lawetlat'la
(Saint Helens)
Klickitat (Adams)
N
0 30 60 90 120 150 180
Kilometers
b
0 40 80 120
Kilometers
c
0 40 80 120
Kilometers
BC
WA
OR
Study Area
A. Revisits to Historical Collection Sites 2021-2022
Found
Not Found
New
Historical Pseudocyphellaria rainierensis collection sites (1948-2016)
B. Review of Forest Inventory Analysis (FIA) Data
FIA plots with records for Pseudocyphellaria rainierensis
FIA plots
C. Review of iNaturalist Observations
iNaturalist observations representing new records
Historical Pseudocyphellaria rainierensis collection sites (1948-2016)

Fig. 1

Maps displaying results from revisits to historical collection sites, review of data from the United States Forest Service's Forest Inventory & Analysis program (USFS FIA) and community science platform iNaturalist **a** *Pseudocyphellaria rainierensis* was recovered at 18 (green circles) of 31 historical collection sites during revisits conducted from 2021 - 2022. Four new sites (yellow stars) were located during focused and opportunistic surveys. Unique occurrence records (gray triangles) represent filtered and thinned data from the Consortium of Lichen Herbaria, National Park Service, and United States Forest Service's Threatened, Endangered and Sensitive Species (TES) and Forest Inventory & Analysis (FIA) programs **b** Review of FIA records found that *P. rainierensis* has only been found in eight (blue circles) of the 664 FIA plots within our study area (gray triangles) **c** Review of iNaturalist observations identified eight observations (yellow circles) that represent new sites for the species, historic collection sites are represented by gray triangles


a
b
c
d
e
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g
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i

Fig. 2

In situ photographs of *Pseudocyphellaria rainierensis* thalli from historical collection sites where the species was relocated. This series provides perspective on morphological variation in the species **a** Elliot Creek: Mount Baker Snoqualmie National Forest, North Cascades. Large group of strappy thalli **b** Colonel Bob: Colonel Bob Wilderness, Olympic Peninsula. Single large thallus. The ruler pictured measures 15.24 cm **c** Tahoma Creek: Mount Rainier Wilderness, Mount Rainier. Growing alongside lookalike and commonly co-occurring species *Lobaria oregana*. **d** Cedar Flats: Gifford Pinchot National Forest, South Cascades. Wet specimen **e** Hoh Creek. Daniel J. Evans Wilderness, Olympic Peninsula. A rosette-forming thallus. **f** Huckleberry Creek: Mount Baker-Snoqualmie National Forest, North Cascades. Minute, strappy thalli **g** Dingford Creek: Alpine Lakes Wilderness, North Cascades. Detail of overlapping strappy thalli. **h** South Fork Cascade River, Glacier Peak Wilderness, North Cascades. Detail of white, underside with pseudocyphellae **i** Tahoma Creek, Mount Rainier Wilderness, Mount Rainier. Detail of thallus with dense, coralloid isidia

When grouped by region, the North Cascades had the largest number of *Pseudocyphellaria rainierensis* sites (61), followed by the South Cascades (43) and the Olympic Peninsula (34), with Mount Rainier region having the fewest number of sites (5). In terms of our survey coverage (in decreasing order), 80% of known sites in the Mount Rainier region, 29% known sites in the Olympic Peninsula region, 20% in the North Cascades region, and 12% of known sites in the South Cascades. The Northern Cascades and Olympic Peninsula had the highest number of sites where we did not relocate *P. rainierensis*. Notably, we did not recover *P. rainierensis* from the five most northerly historical collection sites in Whatcom County. Other areas of low recovery were the northern and western portions of the Olympic Peninsula (Clallam and Jefferson counties) (Figure 1). It's difficult to estimate the full extent and health of *P. rainierensis* populations in the South Cascades region because we visited only 12% of known sites in this region. Additional surveys will be necessary to accurately estimate current population status and abundance of *P. rainierensis* in the South Cascades. We did not detect *P. rainierensis* at two of four Mount Rainier sites which represents losses at 40% of the known sites in this region. However, a recent lichenological study conducted in Mount Rainier National Park found large healthy thalli on multiple trees along the Ohanapecosh river near the type locality, which is a good indication that some populations in this region have remained stable over the last 70+ years (Siskiyou BioSurvey 2024).

Data cleaning of all available FIA records for Region 6 (Washington and Oregon) resulted in 664 plots in Washington west of the Cascade Crest surveyed between 1993 and 2012. *Pseudocyphellaria rainierensis* was present in eight of the 664 FIA plots (Figure 1B, Appendix 3). All of these plots were in old-growth forests. Five of the eight plots were located within protected land classifications such as Wilderness Area, while three of the plots were located within National Forests. One of the plots, located in the Glacier Peak Wilderness, was within ~120 meters of the 2020 Downey Creek Fire which burned approximately 1,112 hectares. We revisited three of these eight sites, namely, Cedar Flats Research Natural Area, Colonel Bob Wilderness, and Gifford Pinchot National Forest, recovering the species at all three locations.

We discovered four previously undocumented *Pseudocyphellaria rainierensis* populations during our opportunistic surveys in the Olympic National Park and central Mount Baker-Snoqualmie National Forest. (Figure 1A, Table 1). At three of the new sites (Chikiman, Success Creek and Staircase) populations were relatively small (between 3-10 small thalli recorded), suggesting these sites may represent recently established or declining populations. At the fourth new site (north fork of Sauk River), *P. rainierensis* thalli were found to be common and robust in size suggesting this site represents a more stable, historical population. Our iNaturalist search yielded 21 observations of *P. rainierensis* made from 2021 - 2024, with 11 of those observations made as part of this research. Processing the 10 remaining observations revealed that eight represent new localities for the species in Washington (Figure 1C, Appendix 4). Four of these new localities are within 1.5 km of historical collection sites, while the remaining four are situated at distances of 5.5 km, 6.5 km, 14.2 km, and 16.3 km from known *P. rainierensis* sites.

With regards to land use designation, 10 of the 18 *P. rainierensis* populations that we successfully relocated in our study were within Wilderness Areas, while the remaining eight were found in National Forests (Figure 1A, Table 1). Of the 13 sites where *P. rainierensis* was not relocated, six were within National Parks or Wilderness Areas while seven sites were in National Forests.

3.2 Habitat Characteristics

Pseudocyphellaria rainierensis was primarily associated with *Tsuga heterophylla/Polystichum munitum* and *Abies amabilis/Vaccinium ovalifolium* vegetation zones in our study (Franklin and Dyrness 1988). We also found that *P. rainierensis* was associated with *Alnus rubra/Rubus spectabilis and Alnus rubra/Acer circinatum* vegetation zones. Percent canopy cover ranges from 55 to 84% at sites where *P. rainierensis* occurred in our study and elevation ranged from 272 to 774 m. The mean annual temperature at sites where *P. rainierensis* was relocated ranged from 5.6 to 8.9 °C. Annual precipitation at *P. rainierensis* sites ranged from 1446 to 3002 mm per year. The wettest month ranged from 230 to 483 mm of precipitation at sites where *P. rainierensis* was recovered, while the driest month was 26 to 58 mm of precipitation (Table 2).

Table 2 Summary of 31 survey sites and percent recovery of *Pseudocyphellaria rainierensis* organized by geographical area in Washington state, USA. The asterisk symbol (*) specifies land use designations which are not protected from commercial logging. This includes National Forest lands, as well as lands managed by the Washington State Department of Natural Resources, Olympic Experimental State Forest, Cedar River Municipal Watershed and the City of Seattle

Region	Land Use Designation	Previously Known Unique Localities	Percent Revisited	Number of Sites Revisited	Found	Not Found
Mount Rainier	Mount Rainier National Park	1	100	1	0	1
	Mount Rainier Wilderness	4	75	3	2	1
	Mount Rainier Subtotal	**5**	**80**	**4**	**2**	**2**
North Cascades	Alpine Lakes Wilderness	5	40	2	2	0
	Cedar River Municipal Watershed*	1	0	0	NA	NA
	Glacier Peak Wilderness	9	11	1	1	0
	Henry M. Jackson Wilderness	1	100	1	1	0
	Mount Baker-Snoqualmie National Forest*	30	20	6	3	3
	Private Lands*	1	0	0	NA	NA
	Ross Lake National Recreation Areas	2	50	1	0	1
	Stephen Mather Wilderness	2	50	1	0	1
	Wild Sky Wilderness*	9	0	0	NA	NA
	Noisy-Diobsud Wilderness	1	0	0	NA	NA
	North Cascades Subtotal	**61**	**20**	**12**	**7**	**5**

Olympic Peninsula	Colonel Bob Wilderness	4	50	2	2	0
	Daniel J. Evans Wilderness	18	17	3	2	1
	Olympic National Forest*	9	22	2	1	1
	Olympic National Park	2	100	2	0	2
	Olympic State Experimental Forest*	1	100	1	0	1
	Olympic Peninsula Subtotal	**34**	**29**	**10**	**5**	**5**
South Cascades	Cedar Flats Research Natural Area	3	33	1	1	0
	Gifford Pinchot National Forest*	39	10	4	3	1
	Goat Rocks Wilderness	1	0	0	NA	NA
	South Cascades Subtotal	**43**	**12**	**5**	**4**	**1**
Washington State Totals		**143**	**22**	**31**	**18**	**13**

Of the 18 sites where we recovered *Pseudocyphellaria rainierensis*, 14 are considered old-growth/climax forest type, six sites are considered late seral, and one site, an *Alnus rubra-Thuja plicata* dominated forest site along Tahoma Creek in Mount Rainier National Park, is considered mid to late-seral forest type; it should be noted that this site was surrounded by old-growth/climax forest. Photographs highlighting habitat types where the species was recovered are presented in Figure 3.

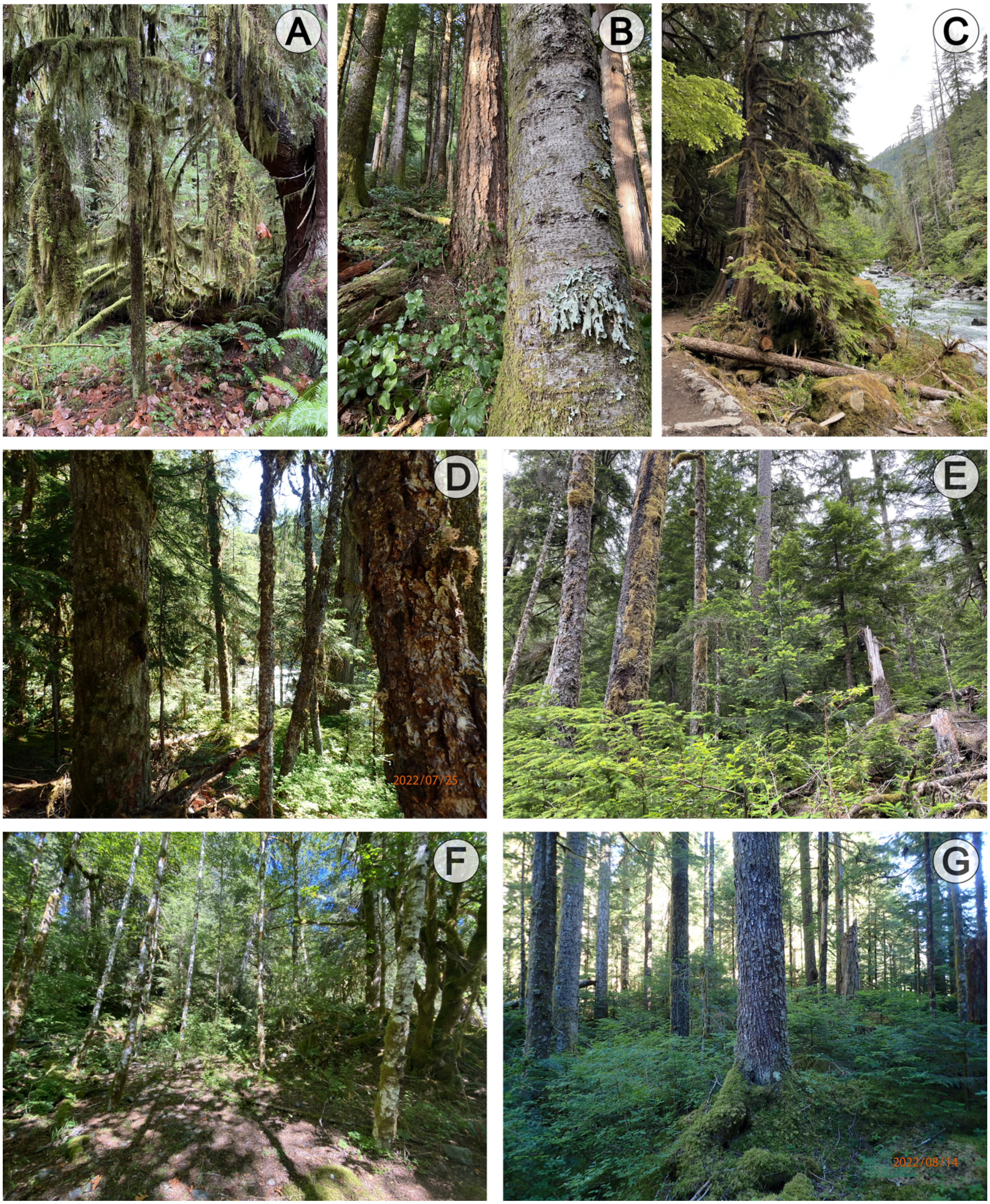

Fig. 3

This photograph plate highlights a selection of habitat types found at historical collection sites where *Pseudocyphellaria rainierensis* was recovered during our revisits. **a** Cedar Flats: Gifford Pinchot National Forest, South Cascades. Old-growth *Tsuga heterophylla/Polystichum munitum/Adiantum aleuticum* forest located on a footslope with complex understory **b** Colonel Bob: Colonel Bob Wilderness, Olympic Peninsula. Old-growth *Tsuga heterophylla - Abies amabilis/Polystichum munitum - Vaccinium ovalifolium* forest located on a midslope terrace with an open, parkland-like understory. **c** Staircase: Daniel J. Evans Wilderness, Olympic Peninsula. Old-growth *Tsuga heterophylla-Thuja plicata/Polystichum munitum - Achlys triphylla* stand with strong riparian influence where the species was recorded for the first time during an opportunistic survey (new site reported in this study) **d** Panther Creek: Mount Rainier Wilderness, Mount Rainier. Late-seral mixed conifer (*Callitropsis nootkatensis - Tsuga heterophylla*) rocky, open bluff with *Vaccinium* spp. understory at the confluence of Panther Creek and the Ohanapecosh River (type specimen locality, Imshaug 598, UM) **e** Dingford Creek: Alpine Lakes Wilderness, North Cascades. Late-seral/old-growth mixed conifer (*Tsuga heterophylla - Abies amabilis - Thuja plicata*), midslope above a small waterfall **f** Hoh Creek: Daniel J. Evans Wilderness, Olympic Peninsula. Old-growth *Tsuga heterophylla/Polystichum munitum/Achlys triphylla - Oxalis oregana* forest with scattered *Acer macrophyllum* and patchy stands of *Alnus rubra* found spanning from a toeslope to riverbed of the Hoh River **g** South Fork Cascade River: Glacier Peak Wilderness, North Cascades: Late-seral conifer stand (*Tsuga heterophylla - Abies amabilis/Vaccinium ovalifolium/Cornus canadensis*) at the confluence of the South Fork and Middle Fork Cascade Rivers

Tsuga heterophylla was present at 100% of the sites where *Pseudocyphellaria rainierensis* was relocated and was often the dominant tree species in these localities. Not surprisingly, *T. heterophylla* was the most common substrate for *P. rainierensis,* representing 89% of all substrate occurrences (17 sites). Other substrates for *P. rainierensis* included *Alnus rubra* (6 sites), *Abies amabilis* (5 sites), *Thuja plicata*, *Acer circinatum* (2 sites), and *Taxus brevifolia* (1 site). *Thuja plicata* was present at 81% of the sites where *P. rainierensis* occurred. The understory shrubs *Vaccinium ovalifolium* and *Rubus spectabilis* were common at 76% and 71%, respectively, of the sites where *P. rainierensis* was present. The epiphytes *Isothecium stoloniferum* and *Lobaria oregana* were present at nearly all sites (90%) and the lichens *Platismatia glauca* and *Sphaerophorus tuckermanii* were present at 81% of the sites occupied by *P. rainierensis.* Other commonly associated lichen taxa present in at least 10 of the 18 sites where *P. rainierensis* was recovered include the lichens *Alectoria sarmentosa, Hypogymnia appinata, Lobaria pulmonaria,* and *Peltigera brittanica.* Other commonly plants included the moss *Hylocomnium splendens* and vascular species *Abies amabilis, Struthiopteris spicant, Cornus canadensis, Disporum hookeri, Linnea borealis, Oploplanax horridus, Polystichum munitum, Rubus pedatus, Tiarella trifoliata, Vaccinium parvifolium.* For a comprehensive list of all vegetation and habitat characteristics, see Appendix 2.

4. Discussion

4.1 Declines are occurring across the species range, regardless of the degree of protection

Our results show that *Pseudocyphellaria rainierensis* populations declined by 41% of the sites we resurveyed at the heart of its range in Washington state. This is a surprisingly high decline given that nearly half of the sites where *P. rainierensis* was not recovered were within National Parks and Wilderness Areas, where logging is not permitted. Similar levels of population decline have been observed for *Usnea longissima* in protected forest reserves in Sweden (Esseen et al. 2023). Our results also show significant population declines in National Forests, despite protections afforded under the Northwest Forest Plan "Survey and Manage" program (USDA Forest Service & BLM 2001). Failure to uphold the monitoring and management guidelines outlined by this plan has led to these declines going undetected for decades. Prior to this study, the majority of known *P. rainierensis* sites within National Forests have not been resurveyed in over 20 years, and the *P. rainierensis* type locality in over 70 years, despite the "Survey and Manage" program and conservation assessments specifying the need for monitoring (Glavich 2013; Sillett and Goward 1998). These findings underscore the critical need for forest managers to regularly monitor *P. rainierensis* populations, even on protected lands, as well as plan for strategic surveys to identify new locations where this species may occur.

A number of factors could explain the observed *Pseudocyphellaria rainierensis* population declines including environmental stochasticity (Öckinger and Nilsson 2010), increased air pollution (McCoy et al. 2021) and climate-driven factors (Allen and Lendemer 2016; Ellis 2013; Ellis et al. 2014; Stanton et al. 2023). It is also possible that forest structural changes obscured detection of *P. rainierensis* at certain sites, leading to unsuccessful search efforts. For example, in climax forests, *P. rainierensis* may still be present in the canopy but difficult to detect in the absence of litterfall. Also, some historical records from the 1950's listed *Alnus rubra* as the lichen's substrate. This pioneer tree species favors high light levels and reaches maturity between 60-70 years with a maximum age of about 100 years (Harrington et al. 1994; Worthington et al. 1962). Therefore, it is unlikely that these individual trees persisted at the sites we surveyed in 2021. Imprecise location information from herbarium records may also lead to unsuccessful searches. This is especially true for historical sites that were recorded prior to modern GPS technologies (Hammerson 2020). More frequent monitoring efforts and a focus on surveying sites that have not been visited in more than 20 years, would increase surveyor confidence in distinguishing between false negatives due to detection error vs. true population losses as a result of habitat changes.

Our analysis of FIA plot survey data revealed the presence of *Pseudocyphellaria rainierensis* in only eight of the 664 forest plots; all of these sites were classified as old-growth forests (Figure 1B). One critique of rare lichen conservation assessments is the inherent bias of search methods that lack standard measures of abundance and specifically focus on one habitat type that the species is known from rather than across a variety of habitat types (Lõhmus and Lõhmus 2009). Given that the FIA forest plots occur in a stratified random grid and represent a standardized lichen inventory method across a wide range of forest ages and forest types, these data reinforce the true rarity of this species and its dependence on old-growth forests for sustaining populations of *Pseudocyphellaria rainierensis.*

4.2 Fire, logging, and air pollution are the biggest threats

Fire frequency and burn area are predicted to increase in western states like Washington due to heightened drought severity, higher temperatures, and potential decreases in summer precipitation due to climate change (Halofsky et al. 2020). *Pseudocyphellaria rainierensis* populations within the *Abies amabilis* vegetation zone on the west slope of the Cascades in Washington (elevations from 600-1,300 meters) may be at greater risk of climate-driven impacts because this tree species is less physiologically suited to drier conditions and more sensitive to fire (Franklin and Dyrness 1988). Increases in extreme heat events, such as the 2021 Pacific Northwest heat dome, severe drought conditions, and wildfire are expected to alter canopy tree cover impacting understory microclimates, a crucial habitat element for the species (Davis et al. 2019; Still et al. 2023; Wolf et al. 2021).

Logging pressures in the northern part of its range, especially in British Columbia, Canada, and increased climate-driven fires in the southern extent of its range (Oregon, USA) have already led to a significant contraction of the species range (Neilson et al. 2022; Villella et al. 2023). Although the focus of this paper is Washington state, we visited several historical *P. rainierensis* sites in Oregon to assess factors affecting the species at the southern extent of its range. The two southernmost known *P. rainierensis* sites occur in the North Umpqua River drainage in Douglas County, Oregon (CLH 2024). Both sites occur in areas that have experienced logging and recent wildfires. We revisited these sites in the fall of 2022 and *P. rainierensis* was not relocated at either. Another cluster of sites located in the Opal Creek Wilderness in the Willamette National Forest in the central Oregon Cascades was revisited in the summer of 2022. This area is within the boundary of the Beachie Creek fire and the forest cover at these sites has been virtually eliminated along with the known occurrences of *P. rainierensis* (Villella et al. 2023). Based on this anecdotal information, we recommend that researchers conduct a similar revisit study in Oregon to gain an accurate current estimate of *P. rainierensis* populations within the state. Locations in Oregon are at the southern edge of several old-growth associated lichen species ranges, and these populations are at high risk of extirpation due to increased frequency of high severity fire and the continued logging of old-growth forests over the last 40 years (Rosso et al. 2000; Villella et al. 2023).

Despite being listed as a species of Special Concern under the Canadian Species at Risk Act, notable population declines have occurred in British Columbia where logging of old-growth forests on Vancouver Island has garnered significant media attention in recent years (Neilson et al. 2022; SARA Registry 2021). An area of particular impact was Granite Creek (adjacent to Fairy Creek watershed) on southern Vancouver Island, where the largest population of *P. rainierensis* recorded in Canada was found with over 600 individual thalli; unfortunately, that site was clear cut in 2021 and the population was almost certainly extirpated (Elliot 2023; Nielsen et al. 2022).

Air pollution may also be a factor in the observed declines of *Pseudocyphellaria rainierensis* in Washington. Lichens are excellent indicators of air quality, and lichens associated with cyanobacterial symbionts, in particular, are especially nitrogen sensitive (Geiser et al. 2010; Jovan 2008; Petix et al. 2024). In a recent study, N deposition was shown to exceed the 3.1 kg-N ha-1 yr-1 critical load to protect N-sensitive lichen species richness in 11.6% of the forested area within North Cascades National Park, 6.3% in Mount Rainier National Park and 1.5% in Olympic National Park (McCoy et al. 2021). Critical load values also exceeded or were near the N-threshold for shifting lichen community composition to more eutrophic species in a 2010 study across several of our study sites (Geiser et al. 2010).

4.3 Highly connected wilderness areas and late-successional forest reserves (LSR) are essential habitats

Based on our surveys, the South Cascades region of Washington supports one of the most abundant and intact *Pseudocyphellaria rainierensis* populations within its range (Table 1; Figure 1A). The Gifford Pinchot National Forest contains 26 of the 28 historical *P. rainierensis* populations recorded in the South Cascades; the high number of occurrences in this region are likely due to the many mature and old-growth forest stands protected within late-successional reserves (LSR), that exist within a matrix of younger timber rotation forests. These LSR's, which were established under the Northwest Forest Plan, represent substantial habitat for many rare and threatened old-growth dependent species (DellaSala et al. 2022). Unfortunately, *P. rainierensis* populations in this region are at high risk for future declines because of the large proportion of unprotected lands combined with an increase in frequency and severity of wildfire in recent years (Halofsky et al. 2020). Large fires have burned multiple times across large areas (>100,000 acres) between 2001 and 2024. Forest connectivity models illustrate how the transfer of matrix lands (ie. forests where most timber harvest occur) into LSR lands (specifically 72,857 acres of forests over 200 years in age) within the Gifford Pinchot National Forest would protect existing habitat for *P. rainierensis* while contributing to overall forest resilience to wildfire through the creation of cool microclimates provided by older forests (Frey et al. 2016; Halsey 2024).

The interior Olympic Peninsula also supports a high abundance of *Pseudocyphellaria rainierensis* populations within the Olympic National Park, which is likely due to the unique abiotic characteristics and regional conservation efforts in those forests. For example, the Colonel Bob Wilderness envelopes 11,961 acres of temperate rainforest protected under the Wilderness Act of 1964. Because of the high proportion of protected forest designations (National Park and Wilderness) on the Olympic Peninsula, *P. rainierensis* populations in this region will likely be the least impacted by land use changes that could disrupt habitat continuity (i.e. logging). The Mount Rainier region also has one of the highest proportions of protected forests. However, this region has by far the fewest number of *P. rainierensis* sites of any region in the state (5). Mount Rainier National Park, which is type locality for *P. rainierensis,* will be an increasingly important refugia for the species and conservation measures should include routine monitoring population size and health to identify potential declines early.

Long-term conservation of *Pseudocyphellaria rainierensis* will also require the creation of suitable habitats in younger forests. Mature forests, defined as stands between 80 to 200 years old for Douglas-fir forests of the Pacific Northwest, will become the old-growth of tomorrow (Spies and Franklin 1991). Efforts to conserve mature forests on public lands are ongoing in the Pacific Northwest where scientists and conservation groups are documenting timber sales on public lands and advocating for policies that prevent logging (Culhane 2013; Whitesell 2004). Protecting old-growth forests, or even remnant old-growth trees, that occur next to mature forests will be especially important because they act as lichen "seed" banks for younger stands. Many old-growth dependent lichens are dispersal-limited (Sillett et al. 2000) or colonization-limited (Bartemucci et al. 2022). Thus, it is essential to minimize the distance between lichen propagule sources (i.e. old-growth trees) and nearby regenerating forest stands. These practices will be essential for creating new habitats where *P. rainierensis* and other old-growth dependent lichens can establish and thrive.

4.4 What measures are needed to conserve and protect remaining populations of old-growth associated epiphytes?

4.4.1 Preservation of old-growth and riparian forests

Preserving old-growth forests is the most important strategy for protecting remaining *Pseudocyphellaria rainierensis* populations across its range (Glavich 2013; Sillett and Goward, 1998). Wilderness Areas and National Parks afford the highest level of protection for existing old-growth habitats. In Washington state, 45% of the known occurrences of *P. rainierensis* are situated within National Parks or Wilderness Areas; all others occur in National Forests, Experimental Forests or National Recreation Areas, which are vulnerable to logging. Of the 143 known *P. rainierensis* sites in Washington, less than a quarter (~22%) have been revisited in the current study. The "Survey and Manage" provisions of the Northwest Forest Plan were set in place to provide protection for all known *Pseudocyphellaria rainierensis* sites within National Forests (U.S. Department of Agriculture, Forest Service, and U.S. Department of Interior, Bureau of Land Management 1994; 2001). Based on our findings, the surveys and actions needed to protect this species were insufficient. Moving forward, forest managers must prioritize monitoring of historical sites, especially within National Forests, to determine the full extent of *P. rainierensis* declines across the range.

We recommend targeted conservation of riparian forests that are in close proximity to old-growth and late-seral stands, as these habitats serve as important refugia for old-growth dependent lichens, particularly for rare cyanobacteria-associated species (Liden and Hilmo 2005; McCune et al. 2002). In our survey, we found that the majority of *Pseudocyphellaria rainierensis* sites were in close proximity to a river (Table 2). Riparian environments provide ideal lichen growth conditions because they introduce gaps in the forest canopy and high humidity from waterfall "spray zones" and river aerosol (Björk et al. 2009). Alder-dominated riparian forests were found to be an important refugium for old-growth dependent lichens in sub-boreal spruce forests of British Columbia (Doering and Coxson 2010). Our review of habitat and substrate data from *P. rainierensis* historical records provide further support for these findings, where alder appears to be an important substrate.

Protecting old-growth forest stands located in valley bottoms and in toe-slope positions should be considered a high conservation priority for *P. rainierensis* and other old-growth dependent lichen communities. In our study, 21 of the 31 historical *P. rainierensis* sites we visited were classified as either basin floor (ie valley bottom) or toeslope. Old-growth forests in valley bottoms are scarce today because they were often the first to be logged; these highly productive stands produced enormous trees prized for timber and were located on the least steep terrain ideal building roads. Old forest valley bottoms and toe slopes of inland temperate rainforests of British Columbia are known to support rich assemblages of rare cyanobacteria-associated lichens (Radies et al. 2019). These sites may act as a refugia from wildfire because of wet soils and abundant groundwater, leading to the accumulation of an abundance of rare canopy lichens over time (Goward and Arsenault 1999).

4.4.2 Continued monitoring and targeted surveys

We discovered four new sites through opportunistic surveys indicating that additional searches in suitable habitats are needed to document the full extent of the species range. This approach has proven to be a successful strategy for evaluating the current status of rare lichen species and characterizing the habitats that sustain existing populations (McMullin 2015; Tagirdzhanova et al. 2019). Eight new *P. rainierensis* locations were also reported on iNaturalist, reinforcing the value of community science efforts in supporting rare species tracking and conservation, particularly when that species is easy to detect (ie. large size, distinctive color, few look-alikes, grows in lower to mid-canopy) (McMullin and Allen 2022; Næsborg 2024; Neilson et al. 2022). More detailed surveys are needed for the *P. rainierensis* sites recorded in iNaturalist to document population size and habitat characteristics.

Overall, the discovery of new *Pseudocyphellaria rainierensis* sites is a positive sign that with targeted search efforts additional locations may continue to be found. However, this cannot discount the dramatic population declines documented in this study and other recent studies (Neilson et al. 2022; Villella et al. 2023). The new sites described in this study do not expand the known range extent of the species and more work is needed to understand the impacts of extinction debt owed from recent large-scale wildfires that destroyed large populations (Kuussaari et al. 2009; Öckinger and Nilsson 2010), as well as the life history and generation time of *P. rainierensis*. This information will be critical for modeling future population declines and recovery rates.

The largest proportion (40%) of all known historical *P. rainierensis* sites in Washington state occur in the North Cascades region (Figure 1). We revisited only a fraction of these sites in the current study (20/61 sites; ~30%) and of the sites we surveyed, *P. rainierensis* was absent from 42% (Table 1). This region is particularly vulnerable to future population declines because of the continuous threats of logging and wildfire combined with reported air quality declines in this region (McCoy et al. 2021; Petix et al. 2025). We recommended a complete inventory of the remaining 30 historical *P. rainierensis* sites in the North Cascades and central Mount Baker-Snoqualmie National Forests to determine the full extent of declines in the northern part of the range.

4.5 Implications for other old-growth associated lichens in the Pacific Northwest

Our results indicate that significant population declines may also be occurring for other old-growth associated lichen species in the Pacific Northwest bioregion. For example, *Nephroma occultum* has a similar status as *P. rainierensis* in the Northwest Forest Plan (Category A) and is considered at high risk of extinction in Washington state due to its restricted range, few occurrences and severe threats to remaining populations (Sillett and Goward 1998; WHNP 2024). Surveying for *N. occultum* presents a particular challenge for forest managers because the species typically grows in the mid- to upper canopy of very old forests and requires either opportunistic litterfall or tree-climbing to estimate population sizes (Rosso et al. 2000). Similar to our *P. rainierensis* surveys, recent revisits to historical *N. occultum* sites found that several populations in Oregon and Washington have been eliminated due to wildfire and logging (pers. comm. J. Villella and J.E.D Miller 2025; J.E.D. Miller 2024) including the southern-most known population in the North Umpqua River drainage in Douglas County, Oregon. Considering that eleven Category A lichen species hold a similar conservation status to *P. rainierensis* and are likely declining without documentation or detection this entire unique and ecologically essential community should be considered threatened. Because lichens share symbionts, species that are not yet threatened are likely to be negatively impacted by declines of other species, leading to extirpation vortices (Allen and Scheidegger 2022; Hestmark et al. 2016). Beyond biodiversity loss the declines in epiphytic lichen communities will lead to major perturbations to carbon and nitrogen cycles and lack of food and nesting material for invertebrates and vertebrates in temperate rainforests of the Pacific Northwest (Asplund and Wardle 2017; Pike 1978; Sharnoff 1994).

5. Conclusions

Monitoring for rare species presents many challenges for forest managers who are tasked with the coordination and implementation of complex forest management plans. This often requires balancing social and economic goals (ie timber sales, recreation) with monitoring and protection of multiple rare species and habitats. These goals are further encumbered by limited staff and funds to carry out these plans. It’s often not realistic for managers to conduct comprehensive monitoring of rare species over millions of acres of public lands. Our study offers a model of how scientists from academic institutions, government and conservation organizations can partner to achieve targeted conservation goals. Indeed, this was the driving factor for the formation of the Nature Conservancy's Natural Heritage Program (now managed by individual states), which stemmed from the need to gather and organize the best available scientific information as the foundation for making sound conservation decisions (Groves et al. 1995). Studies like this one, completed through public-private partnerships, have far-reaching impacts not only for the target species being studied, but also for protecting biodiversity within increasingly threatened ecosystems. By ensuring that old-growth temperate rainforests of the Pacific Northwest continue to exist, we not only protect lesser-known threatened species like *Pseudocyphellaria rainierensis,* but we also conserve habitats that provide important ecosystem services (Brandt et al. 2014), mitigate climate change through carbon storage (Keith et al. 2009; Smithwick et al. 2002) and thermal buffering (Frey et al. 2016), and protect federally threatened species such as the northern spotted owl (USFWS 1990).

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CRediT authorship contribution statement

Conceptualization: J. L. Allen, L. M. Calabria, S. T. Sharrett, J. Villella; Methodology: L. M. Calabria, S. T. Sharrett; Formal analysis and investigation: L. M. Calabria, S. T. Sharrett, J. Villella, F. Waldear; Writing - original draft preparation: L. M. Calabria, S. T. Sharrett, J. Villella; Writing - review and editing: J. L. Allen, L. M. Calabria, S. T. Sharrett, J. Villella; Funding acquisition: J. L. Allen, L. M. Calabria, S. T. Sharrett; Visualization: S. T. Sharrett; Resources: L. M. Calabria; Supervision: J. L. Allen, L. M. Calabria; Project administration: L. M. Calabria

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Declaration of Competing Interests

The authors have no known competing interests.

Data Availability

The datasets generated during and/or analyzed as part of this study are available from the corresponding author on reasonable request due to the conservation status of the study species and sensitive nature of those datasets.

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