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Assessing the gap between conservation need and protection status for select rare ecosystems in Alaska

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Abstract
Rare ecosystems support unique assemblages of flora and fauna within a small geographic area. As such, their conservation represents an effective method of biodiversity protection. The description, mapping, and assessment of rare ecosystems is a necessary and initial conservation action, yet this has not been completed for Alaska. Here, we provide the first comprehensive treatment of rare terrestrial ecosystems for the state. Thirty-five rare systems, representing different levels of ecological organization and geographic scale, are presented. In addition, a gap analysis was conducted to evaluate the systems' current level of land management protection relative to their conservation need. Eleven of the mapped ecosystems are considered adequately protected, two are moderately protected, and 22 are less protected. Conservation ranks are incongruously aligned with land management protection levels such that the rarest systems are often not well protected and the less-imperiled systems are often well protected. On the ecoregion scale, systems with arctic distributions are less protected than are those with boreal and maritime distributions. This rare ecosystem assessment complements species- and landscape-scale conservation studies previously completed for Alaska. Collectively, the recommendations from these assessments provide a science-based strategy for biological conservation in a vulnerable region of the world.

KEYWORDS
Arctic, Beringian, biodiversity, boreal, Pacific, protection index, rarity

1 | INTRODUCTION

From arctic tundra to temperate rainforests, numerous ecosystems span the broad and varied landscapes of Alaska. Ecosystems such as boreal forests and sedge wetlands cover extensive geographic areas of the state and are composed of common species assemblages. In contrast, ecosystems such as karst fens and lodgepole pine woodlands cover small geographic areas and support unique assemblages of species. Because rare ecosystems often contribute disproportionately to regional biodiversity relative to their size, they present a tremendous opportunity for conservation (Gaston, 1994). However, these same systems may be poorly described and mapped, which has implications for their management, protection, and long-term persistence (Williams, Wiser, Clarkson, & Stanley, 2007). Such geographically-restricted ecosystems are likely to face more severe consequences and have a higher probability of extirpation from threats relative to widespread ecosystems (Cole & Landres, 1996; M. C. Wilson et al., 2016).

Determining which elements of regional biodiversity are most vulnerable to threats is critical to their conservation (NatureServe, 2015). Globally, the primary threat to conservation is habitat conversion (Meffe & Carroll, 1997, Wilcove & Master, 2008). While Alaska has been less affected by habitat conversion compared to other states (Duffy, Boggs, Hagenstein, Lipkin, & Michaelson, 1999, Trammell & Aisu, 2015, Reynolds, Trammell, & Taylor, 2018) current and proposed large-scale natural resource extraction activities are affecting more area and habitat types across the state, increasing threats to both rare species (Carlson & Cortés-Burns, 2013) and ecosystems. In the northern latitudes, climate change, rather than direct anthropogenic action, is arguably the primary driver of ecological change (ACIA, 2005, Chapin et al., 2014). Climate change has the potential to threaten the persistence of individual species, as well as the ecology of communities and ecosystems of which they are part (Bjorkman et al., 2018). Furthermore, lands managed for biological conservation may not encompass sufficient components of regional biodiversity. Early conservation efforts in Alaska were often directed towards alpine environments and unique landscape features (Racine & Anderson, 1979, Racine & Young, 1978, Scott et al., 2001, Young & Racine, 1976, 1977), and as a result, currently-protected lands may neither coincide with areas of high terrestrial biodiversity (Smith, Feirer, Hgenstein, Couvillion, & Leonard, 2006), nor harbor individual species of conservation concern (Duffy et al., 1999).

To address potential deficiencies in the recognition of threats and the conservation of biodiversity, we have described, mapped, and evaluated the conservation status of 35 rare terrestrial ecosystems in Alaska at multiple levels of biological and geographical organization. Ecosystems are presented at either the plant association or biophysical setting scale; we use the term "ecosystem" or "system" for their collective reference. Plant associations represent the finest level of vegetation classification and are defined as communities of definite floristic composition and uniform habitat (Flahault & Schroter, 1910; Jennings et al., 2006). Biophysical settings are broader in concept and represent the vegetation that dominates the landscape in the absence of human action for a specific physical environment and natural disturbance regime (Landfire, 2013). These two units of classification differ with respect to heterogeneity and geographic scale. Plant associations typically manifest on the landscape as discrete, spatially-fixed systems, whereas biophysical settings often occupy a greater area and are comprised of more spatially-transitory species assemblages. However, these classification concepts are complementary in so far that plant associations may be used to describe stages within successional sequences or transition models, which in turn, are represented by the greater biophysical setting. While conservation status ranks have traditionally been applied at the species and community levels, we chose to expand the application to biophysical settings in order to capture the full range of environmental conditions and processes thought integral to the development of a rare community, or ecosystem.

The documentation of rare ecosystems at the plant association and biophysical setting scales presented here complements several species- and landscape-scale conservation assessments previously completed for Alaska, such as the Wildlife Action Plan (ADF&G, 2015), Alaska Gap Analysis Program (GAP) Analysis (Gotthardt et al., 2013), Rapid Ecological Assessments (Trammell et al., 2014, Trammell et al., 2016) and the Conservation Blueprint for Alaska (Smith et al., 2006). The collective consideration of these assessments captures a broad swath of ecological organization thereby providing a comprehensive view of rarity and conservation opportunities in Alaska.

2 | METHODS

The identification and description of potentially rare ecosystems in Alaska was an iterative process drawing from the ecological research and expertise of many individuals. To the extent possible, publicly-available data and standardized mapping and ranking methodologies were used to generate the distributions and assess the conservation status of the systems considered in this assessment.

2.1 | Identification and classification of candidate ecosystems

The biophysical settings and plant associations included herein were advanced from a larger pool of candidate systems either described in published literature or recommended by professional ecologists. Candidate ecosystems were evaluated with respect to their composition, defining processes, and representation on the landscape.

Where appropriate, regional designations, such as Arctic, Beringian, Boreal, Aleutian, and Pacific, or a Statewide designation, were assigned to rare ecosystems. These regions, adapted from the Land Resource Regions of Alaska (Moore et al., 2004; Supporting Information) represent areas of broad regional climate and as such, have strong correlation with the natural floristic divisions of Alaska. Broad-ranging biophysical settings with considerable variation in plant community composition were described separately for each region and include a regional designation in their nomenclature (e.g., Arctic Tidal Marshes vs. Beringian Tidal Marshes). Biophysical settings that are not modified by a regional designation are either not restricted to a single geographic region (e.g., Nonvascular Snowbed Plant Associations) or are not significantly influenced by regional floristics (e.g., Geothermal Springs). Short descriptions of each rare ecosystem include an eco-regional designation (Appendix S1).

2.2 | Distribution mapping

Distribution maps for each biophysical setting or plant association were developed using the best-available and most-appropriate geospatial data (Appendix S2). However, because rare ecosystems are often under documented and the sources used to map their occurrences are variable in quality, the accuracy of our mapping is not consistent among systems. Map data were not combined for comparison, we evaluated each systems area of occupancy independently, which allowed us to complete the ranking, establish percent land ownership and provide data on level of protection for each system. The Alaska Vegetation Map provided the basis for the distribution of most biophysical settings (Boggs et al., 2016a, 2016), whereas the locations of characteristic species, as recorded on specimens sourced from the Consortium of Pacific Northwest Herbaria provided the basis for the distribution of most plant associations (CPNWH, 2016). Where these primary sources were not informative to the distribution of a given biophysical setting or plant association, maps were developed from alternate geospatial datasets such as those describing elevation (USGS, 2009; National Elevation Dataset), surface geology (F. H. Wilson, Hults, Mull, & Karl, 2015; Geologic Map of Alaska), wetland type (USDI, 2015; National Wetlands Inventory), glacial extent (GLIMS, 2012), or coastline morphology (NOAA, 2015; ShoreZone). Distribution of the Steppe Bluff Biophysical Setting was modeled in a separate project (Boucher et al., 2014) Using the MaxEnt application (Phillips & Dudík, 2008). We chose a modeled extent of steppe bluff distribution rather than a conventionally mapped distribution because we perceived the documented locations to grossly underestimate the actual number and extent of steppe bluffs and occurrence of the steppe bluff system has been shown to be highly correlated to the climate and landscape features used as model inputs (Boucher et al., 2014). Unless indicated otherwise, all distribution mapping and conservation gap analyses were conducted in a Geographic Information Systems (GIS) environment using ArcGIS 10.4 software.

2.3 | Conservation status ranking

NatureServe's rank calculator (version 3.186) was used to assign preliminary conservation status to biophysical settings and plant associations (Faber-Langendoen et al., 2009; Master et al., 2012). This methodology, developed as a globally-applicable, standard ranking system sums weighted values for factors related to rarity, trends, and threats to calculate conservation status. The rarity of a system is derived from its direct area of occupancy (i.e., distribution), estimated percent of current area occupied considered to have good ecological integrity and geographical range. Unless more spatially-specific information was available (i.e., published accounts of range), range was calculated as a convex-hull polygon encompassing all occurrences of the system using the minimum bounding geometry tool available in ArcGIS. The trend of a system relates to expected change in area of occupancy across the short- (50 years) and long- (200 years) terms and was estimated based on our ecological understanding as well as potential threats to a given system. Threats to a system consider the severity, scope, impact, and timing of stressors, as well as the response and resilience of the system to those stressors. Threats were assessed by best professional judgment with adherence to the guidance provided within the ranking calculator (Master et al., 2012). The range of possible status ranks generated by the rank calculator are: 1—critically imperiled, 2—imperiled, 3—vulnerable, 4—apparently secure, 5—secure, and are preceded by a letter reflecting the appropriate geographic scale of the assessment: G—global, N—national, or S—subnational (i.e., state). Ranks were adjusted from the preliminary, calculated rank if justified by professional judgment or expert opinion. Plant associations and biophysical settings were considered of conservation concern when assessed to be less than secure at the state level (i.e., ≤S4), following the principle of precaution (O'Riordan & Cameron, 1994) and allowing for a broader concept of ecosystem rarity for a large state with high levels of ecosystem intactness (Reynolds et al., 2018), but facing threats that impact large geographies (i.e., climate change).

2.4 | Gap analysis

The GAP, administered by the U.S. Geological Survey (USGS), is a nationwide program that aims to assess the extent to which species and plant communities are represented within protected areas (Scott et al., 1993). To support this goal, USGS developed the Protected Areas Database (PAD-US), which serves as the official inventory of terrestrial and marine protected areas dedicated to the preservation of biological diversity (USGS, 2016). The PAD-US geospatial layer is attributed by a GAP status code, which is determined by land management category, defaults to a minimum level of conservation, and can be used as a proxy for management intent (Table 1) (USGS, 2013).

To evaluate the gaps in protected areas, we intersected each system's distribution with the PAD-US version 1.4 layer developed for Alaska (USGS, 2016). Prior to this intersection, we "flattened" the protected areas layer to remove

TABLE 1 National Gap Analysis Program protection status codes and definitions, as derived from the Protected Areas Database of the United States (PAD-US) version 1.4 geodatabase and conservation status of land management categories ordered by level of designation

Status code	Management definition	Disturbance
1	Managed for biodiversity	Disturbance events proceed or are mimicked
	An area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a natural state within which disturbance events (of natural type, frequency, intensity, and legacy) are allowed to proceed without interference or are mimicked through management.	
2	Managed for biodiversity	Disturbance events suppressed
	An area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a primarily natural state, but which may receive uses or management practices that degrade the quality of existing natural communities, including suppression of natural disturbance.	
3	Managed for multiple uses	Subject to extractive (e.g., mining or logging) or OHV use
	An area having permanent protection from conversion of natural land cover for the majority of the area, but subject to extractive uses of either a broad, low-intensity type (e.g., logging, OHV recreation) or localized intense type (e.g., mining). It also confers protection to federally listed endangered and threatened species throughout the area.	
4	No known mandate for protection	Unknown
	There are no known public or private institutional mandates or legally recognized easements or deed restrictions held by the managing entity to prevent conversion of natural habitat types to anthropogenic habitat types. The area generally allows conversion to unnatural land cover throughout or management intent is unknown.	

Land management category	GAP status code
National designations	
National Park	2
National Forest-National Grassland	3
National Trail	4
National Wildlife Refuge	2
National Natural Landmark	2
National Landscape Conservation System—Non wilderness	3
National Landscape Conservation System—Wilderness	2
Native American Land	4
Other designations	
Protective Management Area—Feature	3
Protective Management Area—Land, Lake, or River	3
Habitat or Species Management Area	2
Recreation Management Area	3
Resource Management Area	3
Wild and Scenic River	2
Research and Educational Land	3
Marine Protected Area	3
Wilderness Area	1
Area of Critical Environmental Concern	3
Research Natural Area	2
Historic/Cultural Area	3
Mitigation Land/Bank	3
Military Land	4
Watershed Protection Area	3
Access Area	4
Special Designation Area	3
Other Designation	4
Not Designated	4
State designations	
State Park	3
State Forest	3
State Trust Lands	3
State Other	4
Local government designations	
Local Conservation Area	2
Local Recreation Area	4
Local Forest	3
Local Other	4
Private designations	
Private Conservation Land	2
Agricultural Protection Land	4
Conservation Program Land	3
Forest Stewardship Land	3

Abbreviation: GAP, Gap Analysis Program; OHV, Off-highway vehicle.

areas of overlapping conservation status. Specifically, the PAD-US layer was converted from its native vector format to a raster dataset with the GAP status code informing the pixel value. In areas of no overlap the value of the GAP code at the center of the cell was adopted as the pixel value, however, in areas of overlap, the highest level of conservation (i.e., lowest GAP code value) was given precedence.

To intersect the PAD-US layer with the 12 systems that were represented by point occurrence data only, it was first necessary to buffer the points. We were able to buffer two of the systems (Arctic Pingos Biophysical Setting and Mud Volcano Biophysical Setting) using literature-supported values, however, for the remaining 10 systems we were forced to adopt estimated areas of occupancy. A 0.01 km^2 area of occupancy (corresponding to a buffer value of 56.4 m) was used for the *Andreaea bylttii* Snowbed Plant Association based on personal observation (Flagstad & Boucher, 2015). An estimated area of 0.3 km^2 (corresponding to a buffer value of 309 m) was used for the *Luzula confusa—Poa arctica*, *Luzula confusa—Sphaerophorus globosus,* and *Papaver gorodkovii* Volcanic Scree Plant Associations and was based on a professional judgment of average area ranging from 0.1 to 0.5 km^2. The remaining six systems: namely the *Artemisia arctica—Trisetum spicatum* Nunatak, *Picea sitchensis/Oplopanax horridus/Circaea alpine*, and *Picea sitchensis/Calamagrostis nutkaensis* Plant Associations and the Geothermal Spring, *Larix laricina* Wetland, and *Picea glauca* Floodplain Old-growth Forest Biophysical Settings were thought to occupy a larger per-occurrence area and thus assigned a default 0.1 km^2 area of occupancy (corresponding to a buffer value of 564 m).

The final output for each ecosystem represented the portion of the PAD-US raster that was spatially-coincident with the distribution of the system. For each PAD-US extraction we calculated the percent area of each GAP status category and calculated a status-weighted protection index for each ecosystem, in accordance with the following formula:

$$Index = \frac{(1*\%Area_{Status1}) + (2*\%Area_{Status2}) + (3*\%Area_{Status3}) + (4*\%Area_{Status4})}{100}$$

This index provides a continuous-variable metric of protection for each ecosystem. Index values have the same range as, and are thus easily compared to, the categorical GAP status codes. For example, an ecosystem-wide score of 1.0 indicates that the entire rare ecosystem is managed for biodiversity (e.g., the entirety of the system is within Wilderness Area boundaries), while a score of 4.0 indicates that no known management mandate for protection has been issued for any part of that ecosystem's extent (e.g., the system occurs only on private lands).

Since determining what constitutes sufficient protection of fine-scale ecosystems occupying a small proportion of the landscape is difficult, we used both protection index and percent of area managed for biodiversity (Status Codes 1 and 2) to summarize conservation status. Systems with a protection index less than 2.5 or at least 50% of their area managed for biodiversity were considered sufficiently protected. This percent area threshold is adopted from literature recommendations (Noss et al., 2012) and represents an approximate average percent of terrestrial land required to meet conservation goals as derived from numerous evidence-based assessments (e.g., scientific research, reviews, and expert opinion).

To assess the levels of spatial organization represented by plant associations and biophysical settings, we placed each system in a local-, intermediate-, or coarse-geographic scale category in accordance with the parameters set forth by Poiani et al., (2000) where local scale refers to a discrete, geomorphologically-defined, and spatially-fixed ecosystem occupying meters to thousands of hectares; intermediate scale refers to relatively-discrete ecosystems defined by physical factors and environmental regimes and occupying hundreds to tens of thousands of hectares, and; coarse scale refers to nondiscrete, ecosystems defined by widespread climatic and elevational gradients and occupying hundreds of thousands to millions of hectares. We considered both area of distribution as well as the ecological characteristics of systems when assigning categories of spatial organization.

We tested for a linear relationship between protection index value and conservation rank of the rare ecosystems using correlation analysis as well as differences in mean conservation rank and mean protection index value among the five geographic groups (Arctic, Beringian, Boreal, Pacific, and Statewide) using analysis of variance (ANOVA) (with Holm-Sidak post hoc tests) and with Kruskal-Wallis ANOVA on ranks for conservation rank data that did not meet normality of variance assumptions.

This paper does not contain any studies with human participants or animals performed by any of the authors.

3 | RESULTS

This assessment of rare ecosystems in Alaska recognizes 23 biophysical settings and 12 plant associations of conservation concern (Table 2) where conservation concern is considered a rank equal to or lower than S4, which is described as "apparently secure—uncommon but not rare; some cause for long-term concern" (Faber-Langendoen et al., 2009). Descriptions summarizing the character, occurrence and conservation status and trend of these ecosystems as well as a list of the candidate ecosystems that were rejected from consideration, are provided in Supporting Information.

3.1 | Distribution mapping

Distribution maps were developed for 34 of the 35 ecosystems considered here (Appendix S1), no rare systems treated here

TABLE 2 Biophysical settings and plant associations of conservation concern for Alaska presented order of decreasing conservation status rank

Ecosystem name	Alaska region	State rank
Artemisia alaskana—Dianthus repens (Alaska wormwood—boreal carnation) Gravel Bar PA	Boreal	S2
Karst Fen BpS	Pacific	S2
Pinus contorta var. latifolia/Cladina species (lodgepole pine/reindeer lichen) PA	Pacific	S2
Picea sitchensis/Oplopanax horridus/Circaea alpina (Sitka spruce/devil's club/enchanter's nightshade) PA	Pacific	S2
Arctic Tidal Marsh BpS	Arctic	S3
Karst *Tsuga heterophylla—Picea sitchensis* (western hemlock—Sitka spruce) PA	Pacific	S3
Larix laricina (tamarack) Wetland BpS	Boreal	S3
Pacific Uplifted Tidal Marsh BpS	Pacific	S3
Papaver gorodkovii (Arctic poppy) Volcanic Scree PA	Beringian	S3
Picea sitchensis (Sitka spruce) Floodplain Old-growth Forest BpS	Pacific	S3
Pohlia wahlenbergii—Philonotis fontana (Wahlenberg's pohlia moss—philonotis moss) Seep PA	Pacific	S3S4
Andreaea blyttii (Blytt's andreaea moss) Snowbed PA	Statewide	S4
Anthelia juratzkana—Gymnomitrion corallioides (liverwort) Biological Crust PA	Pacific	S4
Arctic Barrier Island and Spit BpS	Arctic	S4
Arctic Inland Dune BpS	Arctic	S4
Arctic Pingo BpS	Arctic	S4
Artemisia arctica—Trisetum spicatum (boreal sagebrush—spike trisetum) Nunatak PA	Pacific	S4
Beringian Alpine Limestone *Dryas* BpS	Arctic, Beringian	S4
Beringian Barrier Island and Spit BpS	Beringian	S4
Beringian Dwarf Shrub—Lichen Peatland Plateau BpS	Beringian	S4
Beringian Tidal Marsh BpS	Beringian	S4
Boreal Forested Glacial Ablation Plain BpS	Boreal	S4
Boreal Inland Dune BpS	Boreal	S4
Callitropsis nootkatensis (yellow cedar) Wetland BpS	Pacific	S4
Geothermal Spring BpS	Statewide	S4
Karst Alpine Herbaceous Meadow and Heath BpS	Pacific	S4
Luzula confusa—Poa arctica (northern woodrush—Arctic bluegrass) PA	Arctic	S4
Luzula confusa—Sphaerophorus globosus (northern woodrush—globe ball lichen) PA	Arctic	S4
Mud Volcano BpS	Statewide	S4
Pacific Barrier Island and Spit BpS	Pacific	S4
Pacific Forested Glacial Ablation Plain BpS	Pacific	S4
Pacific Tidal Marsh BpS	Pacific	S4
Picea glauca (white spruce) Floodplain Old-growth Forest BpS	Boreal	S4
Picea sitchensis / Calamagrostis nutkaensis (Sitka spruce / Pacific reedgrass) PA	Pacific	S4
Steppe Bluff BpS	Boreal	S4

are endemic to the Aleutian region (Figure 1). Due to the paucity of geospatial information, we were not able to generate a defensible distribution for the Wahlenberg's Pohlia Moss-Philonotis Moss (*Pohlia wahlenbergii—Philonotis fontana*) Seep Plant Association. Cumulatively, ecosystems of conservation concern represent 3% of the total area of Alaska, with the Yellow Cedar (*Callitropsis nootkatensis*) Wetland Biophysical Setting (1.0%), Beringian Dwarf Shrub-Lichen Peatland Plateau Biophysical Setting (0.8%), Beringian Alpine Limestone *Dryas* Biophysical Setting (0.6%), Beringian Tidal Marsh Biophysical Setting (0.3%), and Pacific Tidal Marsh Biophysical Setting (0.2%) representing the five largest systems. The Arctic Poppy (*Papaver gorodkovii)* Volcanic Scree, Blytt's andreaea Moss (*Andreaea blyttii*) Snowbed, Alaska Wormwood—Boreal Carnation (*Artemisia alaskana—Dianthus repens*) Gravel Bar, and Lodgepole Pine/Reindeer Lichen (*Pinus contorta var. latifolia/Cladina*) species Plant Associations and the Karst Fen Biophysical Setting, represent the four smallest systems with individual areas of 0.5 km^2 or less (Table 3).

3.2 | Conservation status ranking

Conservation status ranks were assigned at the state level to each biophysical setting and plant association. While most ranks were adopted directly from the rank calculator, seven ranks were adjusted based on professional judgment. Revision of the Wahlenberg's Pohlia Moss-Philonotis Moss Seep Plant Association rank represents the greatest change in rank. The calculated rank of S1 was downgraded to an adjusted range rank of S3S4 on the basis that this system is significantly under-surveyed. While less than 20 occurrences have been documented, the component moss species occur throughout the state and are likely to co-occur in other locations along the Aleutian Islands and greater southern Alaska region. Ranks for the Lodgepole Pine/Reindeer Lichen, Alaska Wormwood—Boreal Carnation Gravel Bar, Sitka Spruce/Devil's Club/Enchanter's Nightshade (*Picea sitchensis/Oplopanax horridus/Circaea alpina*) Plant Associations, and the Karst Fen Biophysical Setting were adjusted from the calculated value of S1 to the next lower level of conservation rank (S2) on the assumption that these systems are under-surveyed. Alternatively, the conservation status rank for the Beringian Alpine Limestone *Dryas* and the Pacific Tidal Marsh Biophysical Settings were adjusted from the calculated rank of secure (S5) to apparently secure (S4) on the basis that the areas of occupancy generated for these systems are likely overestimated.

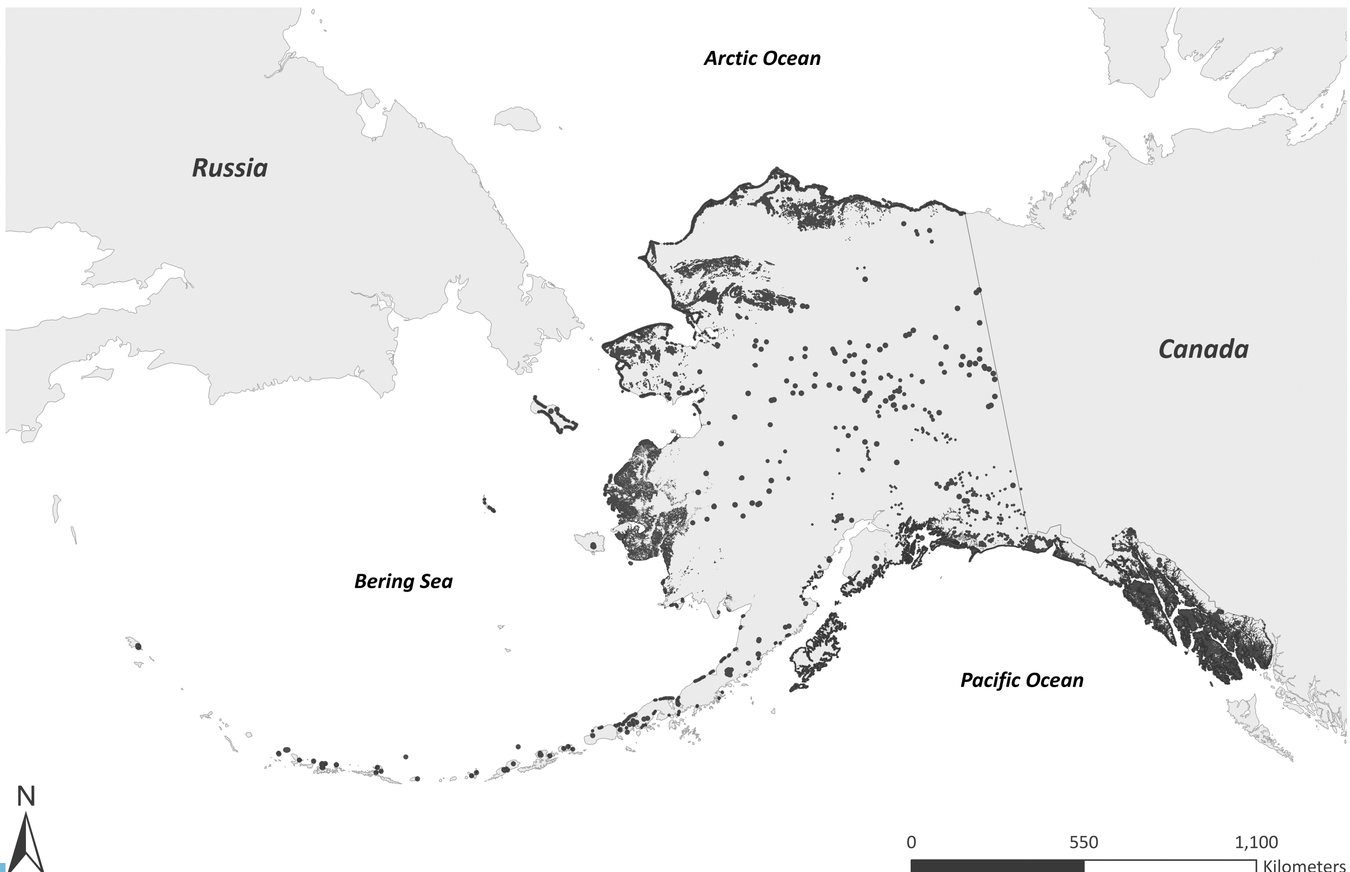

FIGURE 1 Distribution of ecosystems of conservation concern (dark gray) across Alaska

TABLE 3 Alaska's rare ecosystems presented in increasing value of protection index

				Percent area					
Ecosystem name	**Scale**	**Conservation rank**	**Area (km^2)**	**Status 1**	**Status 2**	**Status 3**	**Status 4**	**Protection index**	**Percent area managed for biodiversity (status 1 and 2)**
Anthelia juratzkana—Gymnomitrion corallioides Biological Crust PA	Local	S4	1.1	100.0	0.0	0.0	0.0	1.00	100.0
Boreal Inland Dune BpS	Local	S4	106.6	99.8	0.0	0.0	0.2	1.00	99.8
Artemisia alaskana—Dianthus repens Gravel Bar PA	Local	S2	0.1	89.1	0.0	0.0	10.9	1.33	89.1
Pacific Forested Glacial Ablation Plain BpS	Intermediate	S4	67.0	77.8	0.9	17.0	4.3	1.48	78.7
Artemisia arctica—Trisetum spicatum Nunatak PA	Local	S4	1.5	75.0	0.0	25.0	0.0	1.50	75.0
Boreal Forested Glacial Ablation Plain BpS	Intermediate	S4	7.4	75.3	1.6	4.2	18.9	1.67	76.9
Beringian Dwarf Shrub—Lichen Peatland Plateau BpS	Coarse	S4	10,407.6	67.4	0.0	0.4	32.2	1.97	67.4
Pinus contorta var. *latifolia / Cladina* species PA (Lodgepole pine/Reindeer lichen)	Local	S2	<0.1	0.0	100.0	0.0	0.0	2.00	100.0
Pacific Barrier Island and Spit BpS	Intermediate	S4	178.2	24.0	52.1	10.7	13.2	2.13	76.1
Papaver gorodkovii (Arctic Poppy) Volcanic Scree PA	Local	S3	1.5	60	0.0	0.0	40.0	2.20	60.0
Beringian Tidal Marsh BpS	Intermediate	S4	3,898	56.4	0.0	1.2	42.4	2.30	56.4
Andreaea blyttii (Blytt's andreaea) Snowbed PA	Local	S4	0.2	52.8	0.0	9.2	38.0	2.32	52.8
Picea sitchensis Floodplain Old-growth Forest BpS	Intermediate	S3	466	26	18.4	41.5	14.1	2.44	44.4
Geothermal Spring BpS	Local	S4	102.9	42.2	4.9	13.2	39.7	2.50	47.1
Steppe Bluffs BpS	Local	S4	30.9	37.9	11.8	12.7	37.6	2.50	49.7
Callitropsis nootkatensis (Yellow cedar) Wetland BpS	Intermediate	S4	12,676	25.3	7.3	58.3	9.1	2.51	33.6
Pacific Uplifted Tidal Marsh BpS	Intermediate	S3	554.4	2.5	57.5	23.9	16.1	2.54	60
Beringian Alpine Limestone *Dryas* BpS	Coarse	S4	7,572	40.7	0.0	13.8	45.5	2.64	40.7
Picea sitchensis /Oplopanax horridus /Circaea alpina PA	Local	S2	2.0	12.6	47.4	0	40	2.67	60
Luzula confusa—Sphaerophorus globosus PA	Local	S4	5.7	36.7	0.0	21.1	42.2	2.69	36.7

TABLE 3 (Continued)

Ecosystem name	Scale	Conservation rank	Area (km^2)	Percent area: Status 1	Status 2	Status 3	Status 4	Protection index	Percent area managed for biodiversity (status 1 and 2)
Karst Alpine Herbaceous Meadow and Heath BpS	Intermediate	S4	63.2	10.4	8.2	79.6	1.8	2.73	18.6
Picea sitchensis /Calamagrostis nutkaensis PA	Local	S4	10.0	27.5	0.0	39.1	33.4	2.78	27.5
Karst *Tsuga heterophylla—Picea sitchensis* PA	Local	S3	479.4	17.6	5.3	57.6	19.5	2.79	22.9
Karst Fen BpS	Local	S2	0.2	0.0	0.0	100.0	0.0	3.00	0.0
Pacific Tidal Marsh BpS	Intermediate	S4	3,007	10.2	23.4	11.32	55.1	3.11	33.6
Picea glauca Floodplain Old-growth Forest BpS	Intermediate	S4	351.0	25.5	0.0	12.12	62.4	3.11	25.5
Arctic Inland Dune BpS	Local	S4	92.9	0.0	0.0	77.1	22.7	3.23	0.0
Arctic Pingo BpS	Local	S4	121	2.7	0.0	61.0	36.3	3.31	2.7
Beringian Barrier Island and Spit BpS	Intermediate	S4	118.6	12.2	7.4	2.9	77.5	3.46	19.6
Arctic Tidal Marsh BpS	Intermediate	S3	1,156	5.9	0.33	23.35	70.4	3.58	6.2
Larix laricina Wetland BpS	Local	S3	35.2	8.5	0.8	10.7	80	3.62	9.3
Luzula confusa—Poa arctica PA	Local	S4	7.8	0.0	0.0	23.1	76.9	3.77	0.0
Arctic Barrier Island and Spit BpS	Intermediate	S4	190.4	3.9	0.0	8.7	87.4	3.80	3.9
Mud Volcano BpS	Local	S4	4.7	0.0	0.0	14.7	85.3	3.85	0.0
*Pohlia wahlenbergii—Philonotis fontan*a Seep PA (not mapped)	Local	-	-	-	-	-	-	-	-

Abbreviation: PA, Plant Association.

In total, four systems are designated as imperiled (S2), six systems are vulnerable (S3), one system is vulnerable to apparently secure (S3S4), and the remaining 24 are apparently secure (S4). The most imperiled ecosystems in Alaska as currently assessed are the Lodgepole Pine/Reindeer Lichen Plant Association, the Alaska Wormwood—Boreal Carnation Gravel Bar Plant Association, Sitka Spruce/Devil's Club/Enchanter's Nightshade Plant Association, and the Karst Fen Biophysical Setting.

Alaska's rarest ecosystems differ in physiognomy (e.g., forested and not forested, wetland, and upland), but are largely united by uncommon surficial geologies that are very sporadic and isolated on the landscape. The systems of lesser conservation concern are also associated with uncommon substrates, but either occupy a greater area or geographic range. A single occurrence of the Lodgepole Pine/Reindeer Lichen Plant Association has been documented in southeastern Alaska where stands of this subspecies of tree, which is uncommon in Alaska, develop in deep lichen mats overlying well-drained granitic bedrock outcrops. The Alaska Wormwood—Boreal Carnation Gravel Bar Plant Association has been described from two gravel river bars in subarctic, continental Alaska and is considered rare for both its unusual combination of diagnostic species as well as its restriction to well-drained substrates derived from ultramafic parent materials. Sitka Spruce/Devil's Club/Enchanter's Nightshade Plant Association has only been documented on wind-deposited silt on hillslopes adjacent to the Stikine River delta in southeastern Alaska. Karst fens are considered one of the rarest wetland types in North America and, in Alaska, are represented by only three occurrences located in coastal rainforests overlying calcareous bedrock.

Within each category of conservation rank, both plant associations and biophysical settings are represented.

Likewise, we did not detect a difference in conservation rank among the regions of Alaska (Kruskal-Wallis $X^2 = 3.97$, $p = .41$; (Table 3). One S3 and five S4 systems occur in Arctic Alaska, one S3 and four S4 systems occur in Beringian Alaska, one S2, one S3, and four S4 systems occurring in Boreal Alaska, and three S2, three S3, one S3S4, and eight S4 systems occurring in Pacific Alaska. Only three apparently secure (S4) systems: Blytt's andreaea Moss Snowbed Plant Association, Geothermal Spring, and Mud Volcano Biophysical Settings, have statewide distributions of widely scattered and small areas of occurrence.

3.3 | Gap analysis

Using land ownership and management intent as proxies for level of conservation protection, we found 35% (12 of 34 mapped systems) of rare ecosystems in Alaska have adequate levels of protection (Table 3). Three systems are marginally protected with either 50% of their extent managed for biodiversity or a protection index less than 2.5, but not both. The remaining 19 systems are considered under protected.

The comparison of gap analysis protection index value to conservation rank (S1–S5) (Figure 2 and Tables 2 and 3) shows no detectable relationship between the magnitudes of protection values and conservation ranks (Pearson's $r = .005$, $p = .98$, $n = 34$). Two of the four imperiled (S2) systems, namely the Alaska Wormwood—Boreal Carnation Gravel Bar, and Lodgepole Pine/Reindeer Lichen Plant Associations have a protection index less than 2.5, indicating a high level of protection; the Sitka Spruce/Devil's Club/Enchanter's Nightshade Plant Association has a moderate protection index of 2.67. However, no portion of the

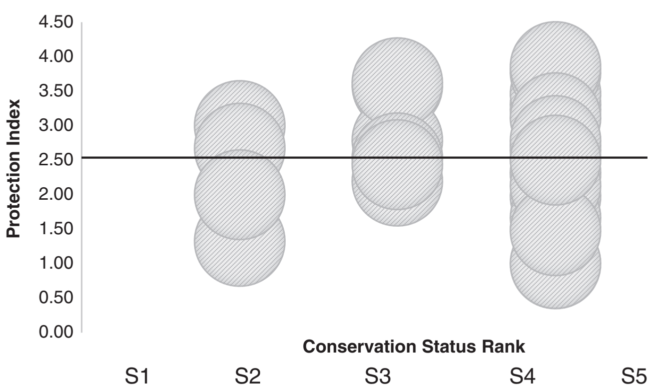

FIGURE 2 Distribution of ecosystems (circles) of conservation concern in Alaska by protection index value and category of conservation status (S1–S5). S1 = "critically imperiled," S2 = "imperiled," S3 = "vulnerable," S4 = "apparently secure," S5 = "secure." The horizontal line indicates a conceptual threshold in biodiversity protection between those deemed "more protected" and those deemed "less protected"

state's most imperiled system, the Karst Fen Biophysical Setting is managed for biodiversity. Only one of the state's six vulnerable (S3) systems are associated with lands that are managed for biodiversity protection, yet nine of 24 apparently secure (S4) systems are afforded adequate protection based on land management designations. Less-protected ecosystems often occur in coastal (e.g., barrier islands, spits, tide marshes) or other accessible, low-elevation areas (e.g., uplifted tidal marshes, and old-growth forests). Conversely, well-protected ecosystems are often found in high-elevation (e.g., alpine and nunatak associations) or otherwise extreme (e.g., xeric, wetland, periglacial, permafrost) environments.

When evaluated by protection index, relatively consistent levels of protection were found among systems with shared environmental factors, processes, or regimes. For example, the protection indices for the Boreal Forested Glacial Ablation Plain and the Pacific Forested Glacial Ablation Plain biophysical settings are similar (1.67 and 1.48, respectively). Also, the related systems of Boreal (where *Picea glauca* is diagnostic) and Pacific (where *Picea sitchensis* is diagnostic) Old-growth Forest Biophysical Settings had similar protection indices of 3.11 and 2.44, respectively. Coastal systems represented by tidal marshes and seaward complexes of barrier islands and spits also show considerable overlap in their range of protection indices. The Arctic, Beringian, and Pacific Tidal Marsh Biophysical Settings have protection indexes averaging 2.99 with range in values from 2.30 to 3.58; whereas the Arctic, Beringian, and Pacific Barrier Islands and Spit biophysical settings have protection indexes averaging 3.13 with range in values from 2.13 to 3.80. Arctic and Boreal Inland Dunes had the greatest spread in protection indexes among environmentally-similar systems at 3.23 and 1.00, respectively.

Ecosystem level of protection is related to region (F [4, 33] = 3.89, $p = .012$). Systems with arctic distributions are not as well-protected as Boreal and Pacific systems (post-hoc Arctic-Boreal Holm-Sidak $t = 3.44$, $p = .018$ and Arctic-Pacific Holm-Sidak $t = 3.14$, $p = .034$). When summarized by region, systems in Arctic, Beringian, Pacific, and Boreal Alaska have average protection indices of 3.4, 2.5, 2.3, and 2.2, respectively.

4 | DISCUSSION

While most rare ecosystems in Alaska are not of immediate conservation concern, only a third of the systems identified here are managed for biodiversity. The remaining two thirds of systems occur in areas without explicit biodiversity protection and thus may be threatened by development or other factors.

The absence of critically imperiled (S1) and the low number of imperiled (S2) and vulnerable (S3) ecosystems identified for Alaska is due in part to low levels of human disturbance, which return modest scores in the threats section of the conservation ranking calculator. Interestingly, the development pattern in Alaska, where the anthropogenic footprint occurs in smaller patches embedded in a breadth of intact ecosystems, is largely reversed from the contiguous United States. However, all ecoregions in the state have some level of human development (Reynolds et al., 2018), and anthropogenic disturbance in natural areas associated with large- and small-scale industry and other forms of development continue. Unchecked, such disturbance will eventually cause adverse effect to under-protected ecosystems of conservation concern.

It is important to note that a designation of “Managed for Biodiversity” in the PAD-US database does not necessarily preclude development. For example, the 1002 Area of the Arctic National Wildlife Refuge, which is ostensibly managed for biodiversity has recently been opened for oil and gas exploration. Similarly, the State of Alaska has requested exemptions (e.g., Alaska Roadless Rule in the Tongass National Forest) from federal conservation policies to promote economic development. Alternatively, federal laws, such as the National Environmental Policy Act, Clean Water Act, Endangered Species Act, and others could afford greater protection to ecosystems under their purview, such as wetlands and riparian floodplains, regardless of land management intent. Because the granting of exemptions and enforcement of regulation often occurs on a case-by-case basis we were not able to consistently account for the effect of individual rulings in this assessment.

Ecosystems of conservation concern vary in physiognomy, spatial extent, and land management status. Thus, the gap between conservation status and current level of protection is easier to close for some systems than for others. For example, the conservation status of systems presumed to be under documented, such as the Lodgepole Pine/Reindeer Lichen and the Alaska Wormwood—Boreal Carnation Gravel Bar Plant Associations, as well as the Karst Fen Biophysical Setting, may be artificially high and thus the gap between status and protection may belie the insecurity of such systems. For discrete systems, such as the Inland Dune, Steppe Bluff, Mud Volcano, and Geothermal Spring Biophysical Settings, a revision of land management intent towards conservation would address the discrepancy between conservation rank and protection status. Climate change resilience for the Boreal Inland Dune or Steppe Bluff systems, for example, can be strengthened by minimizing proximal factors that affect ecosystem vulnerability such as invasive species establishment and off-road vehicle use. Resilience for other discrete ecosystems of conservation concern can be addressed by protection of adjacent landscapes and likely migration corridors. However, providing adequate protection to more widely-distributed systems presents a greater challenge. For example, systems derived from calcareous substrates, such as the Karst Alpine Herbaceous Meadow and Heath Biophysical Setting and the Karst Western Hemlock—Sitka Spruce (*Tsuga heterophylla—Picea sitchensis*) Plant Association have broad geographic range, the protection of which would require increased commitment among multiple landowners within the supporting watersheds. Similarly, systems that develop along major environmental gradients such as barrier islands, spits, and tidal marshes are more difficult to protect as their ecological integrity is often controlled by processes that transcend local control. Conservation strategies developed for tidal wetlands for example, can focus on maintaining biological integrity through cross jurisdictional recognition of the carbon sequestration function of these wetlands. These strategies could include wetland conservation, protection, or restoration, and incorporation of coastal wetlands into the carbon market.

Even more problematic are systems whose existence is reliant on the stasis of a particular climatic regime. The greater rate of climate change at high latitudes (ACIA, 2005; USGCRP, 2018) in combination with the lesser protection of systems with arctic distributions relative to those with boreal and maritime distributions, places the arctic and alpine systems described here at heightened risk. High-elevation, montane systems such as the Beringian Alpine Limestone *Dryas* Biophysical Setting cannot be maintained by up gradient migration indefinitely and similarly, the northward movement of arctic systems such as the Northern Woodrush—Arctic Bluegrass (*Luzula confusa—Poa arctica*) and the Northern Woodrush—Globe Ball Lichen (*Luzula confusa—Sphaerophorus globosus*) Plant Associations will be ultimately curtailed by the Arctic Ocean. Without a northward migration route, individual rare plant species that are currently restricted to the Arctic Coastal Plain in Alaska are projected to face substantial declines in available suitable habitat by 2060 (Carlson & Cortés-Burns, 2013).

The adequate protection of permafrost-dependent systems such as Arctic Pingos and Dwarf Shrub—Lichen Permafrost Plateaus is perhaps most challenging. In just the last 30 years, there has been a 2°C increase in mean annual temperature in the arctic biome (ACIA, 2005) and temperature is predicted to continue to increase more rapidly than at lower latitudes (IPCC, 2007; Chapin et al., 2014). There are numerous examples of shrub and tree expansion in arctic and alpine tundra habitats around the state that in turn drive alterations in ecosystem processes (Klein, Berg, & Dial, 2005; Dial, Berg, Timm, McMahon, & Geck, 2007; Tape, Sturm, & Racine, 2006; Roland, Schmidt, & Nicklen, 2013).

Furthermore, climate change influences the frequency and severity of disturbances, such as insect outbreaks and wildfires (Soja et al., 2006; Chapin et al., 2008) and is likely affecting the establishment rate of non-native species (Carlson & Shephard, 2007; Sanderson, McLaughlin, & Antunes, 2012). These phenomena have direct effect on species and communities and by extension, pose substantial risk to the current composition and function of rare ecosystems. Management action for such ecosystems threatened by climate change may include minimizing compounding local anthropogenic impacts and ensuring protection of adjacent landscapes and likely migration corridors.

As the rate, extent, and severity of global climate change increases, both a commensurate expansion in our concept of adequate conservation (Noss et al., 2012) and facilitation of cross-jurisdictional planning for natural resource management (Trammell, Thomas, Mouat, Korbulic, & Bassett, 2017) are necessary. Local, national, and international conservation that aims to preserve multiscale ecological patterns and processes provides a precautionary approach to sustain the full complement of biota and their supporting natural systems (Poiani, Richter, Anderson, & Richter, 2000). In this assessment of rare ecosystems, we have considered multiple levels of biological and geographical organization ranging from coarse-scale biophysical settings to local-scale plant associations. This multiscale approach identifies systems large enough to protect the ecological processes that support their embedded communities and species while simultaneously capturing species-based or spatially-restricted systems that can be harbingers of greater ecosystem change. Particularly in combination with the species- and landscape-scale conservation assessments that have been previously completed for Alaska, the description, mapping, and conservation gap analysis presented here furthers effective ecological conservation in Alaska. By closing the gap between the conservation need and protection status of Alaska's rare ecosystems we build awareness and capacity to accommodate the growing impacts of changing climate and development in a vulnerable region of the world.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

L.F., A.S., T.B. K.B., M.C., and T.K. provided research on rare ecosystems. B.B. completed the gap analysis and protection indices calculations. P.L. provided mapping support. L.F and A.S. also completed ranking of rare ecosystems. M.C. also provided statistical analysis and manuscript review.

DATA ACCESSIBILITY

All data from this research is openly available from the University of Alaska, Alaska Center for Conservation Science at www.accs.alaska.edu.All data supporting this research is provided as supplementary information accompanying this paper.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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