National Park Service
U.S. Department of the Interior

Natural Resource Program Center

A Natural Resource Condition Assessment for Rocky Mountain National Park

Natural Resource Report NPS/NRPC/WRD/NRR—2010/228

ON THE COVER
Rocky Mountain National Park
Photograph by: Billy Schweiger

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<u>Air and Climate:</u>

- Baron, J. S., K. E. Williams, and M. Hartman. 2010. Condition of alpine lakes and atmospheric deposition. In: A Natural Resource Condition Assessment for Rocky Mountain National Park. Natural Resource Report NPS/NRPC/WRD/NRR—2010/228. National Park Service, Fort Collins, Colorado.

Water:

- Theobald, D. M. and J. B. Norman, III. 2010. Extent and connectivity of wetland and riparian areas. In: A Natural Resource Condition Assessment for Rocky Mountain National Park. Natural Resource Report NPS/NRPC/WRD/NRR—2010/228. National Park Service, Fort Collins, Colorado.

Biotic Integrity:

- Theobald, D. M. and J. B. Norman, III. 2010. Extent of exotic terrestrial plants. In: A Natural Resource Condition Assessment for Rocky Mountain National Park. Natural Resource Report NPS/NRPC/WRD/NRR—2010/228. National Park Service, Fort Collins, Colorado.

- Theobald, D. M. and J. B. Norman, III. 2010. Extent and connectivity of fish distributions. In: A Natural Resource Condition Assessment for Rocky Mountain National Park. Natural Resource Report NPS/NRPC/WRD/NRR—2010/228. National Park Service, Fort Collins, Colorado.

- Scherer, R., I. Leinwand, B. R. Noon, and D. M. Theobald. 2010. Extent of suitable beaver habitat. In: A Natural Resource Condition Assessment for Rocky Mountain National Park. Natural Resource Report NPS/NRPC/WRD/NRR—2010/228. National Park Service, Fort Collins, Colorado.

Landscapes:

- Noon, B. R., D. M. Theobald, and J. Norman, III. 2010. Extent and pattern of major ecological systems. In: A Natural Resource Condition Assessment for Rocky Mountain National Park. Natural Resource Report NPS/NRPC/WRD/NRR—2010/228. National Park Service, Fort Collins, Colorado.

- Theobald, D. M., B. R. Noon, and J. Norman, III. 2010. Connectivity of natural landscapes. In: A Natural Resource Condition Assessment for Rocky Mountain National Park. Natural Resource Report NPS/NRPC/WRD/NRR—2010/228. National Park Service, Fort Collins, Colorado.

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Publisher's Note: Some or all of the work done for this project preceded the revised guidance issued for this project series in 2009/2010. See Prologue (p. xxii) for more information.

Executive Summary

We conducted a natural resource assessment of Rocky Mountain National Park (ROMO) to provide a synthesis of existing scientific data and knowledge to address the current conditions for a subset of important park natural resources. The intent is for this report to help provide park resource managers with data and information, particularly in the form of spatially-explicit maps and GIS databases, about those natural resources and to place emerging issues within a local, regional, national, or global context. With an advisory team, we identified the following condition indicators that would be useful to assess the condition of the park:

- Air and Climate: Condition of alpine lakes and atmospheric deposition
- Water: Extent and connectivity of wetland and riparian areas
- Biotic Integrity: Extent of exotic terrestrial plant species, extent of fish distributions, and extent of suitable beaver habitat
- Landscapes: Extent and pattern of major ecological systems and natural landscapes connectivity

These indicators are summarized in the following pages. We also developed two maps of important issues for use by park managers: visitor use (thru accessibility modeling) and proportion of watersheds affected by beetle kill.

Based on our analysis, we believe that there is a high degree of concern for the following indicators: condition of alpine lakes; extent and connectivity of riparian/wetland areas; extent of exotic terrestrial plants (especially below 9,500'); extent of fish distributions; extent of suitable beaver habitat; and natural landscapes and connectivity. We found a low degree of concern for: the extent and pattern of major ecological systems.

The indicators and issues were also summarized by the 34 watershed units (HUC12) within the park. Generally, we found six watersheds to be in "pristine" condition: Black Canyon Creek, Comanche Creek, Middle Saint Vrain Creek, South Fork of the Cache la Poudre, Buchanan Creek, and East Inlet. Four watersheds were found to have strong restoration opportunities: Big Thompson River West, Cache la Poudre South, Colorado River North, and Onahu Creek. Ten watersheds were found to have substantial near-term issues: Aspen Brook, Big Thompson River West, Black Canyon Creek, Cabin Creek, Cache la Poudre South, Fall River, Hague Creek, La Poudre Pass Creek, North Fork Big Thompson (East), and Colorado River North.

Air and climate: Condition of Alpine Lakes and Atmospheric Deposition

What: Measures atmospheric deposition of nutrients and pollutants in high elevation lakes.

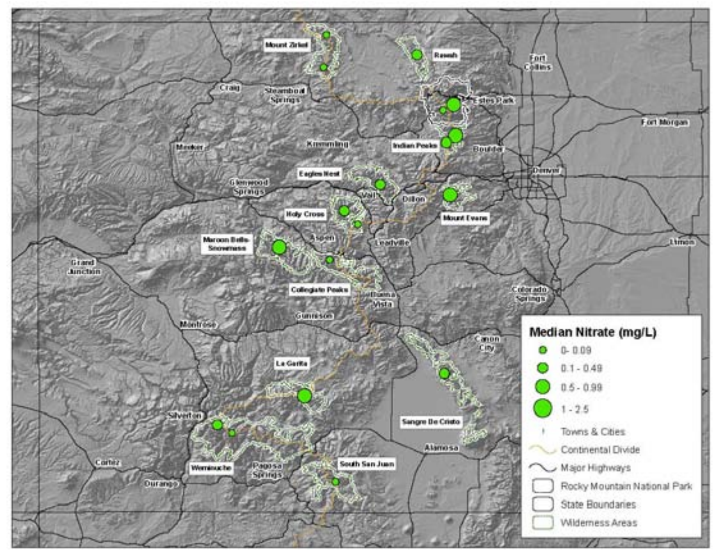
Why: High elevation lakes are bellwethers of ecological change and the extent of human-caused disturbance.

Stressors: Land use change, climate change.

Confidence: High degree of concern; moderate evidence, high agreement.

Atmospherically-deposited nitrogen has caused east-side ROMO lakes to have higher than background nitrate concentrations and lower than expected acid-neutralizing capacity (ANC). East-side concentrations of dieldrin and DDT are also elevated, while west-side mercury in fish tissue is at or above concentrations that are harmful for some birds and mammals. West-side nitrate and ANC are consistent with reference conditions, and lake pH and chemical concentrations of calcium, chloride, sulfate, ammonium for all ROMO lakes are consistent with reference conditions.

Measure	Reference Condition	Current condition	Confidence	Level of Concern
Lake pH	6.5-7.5	6.6 (east) 7.0 (west)	Moderate	High
Lake ANC	80-100 μeq L^{-1}	50 μeq L^{-1}(east) 80 μeq L^{-1}(west)	Moderate	High
Lake ammonium	Below detection limits	0.01 mg L^{-1} (east) 0.01 mg L^{-1} (west)	Moderate	High
Lake nitrate	$\leq$0.1 mg L^{-1}	0.57 mg L^{-1} (east) 0.06 mg L^{-1} (west)	High	High
Lake sulfate	0.2-109.0 mg L^{-1} (all lakes)	1.3 mg L^{-1} (east) 1.5 mg L^{-1} (west)	High	High
Lake chloride	0.03-1.16 mg L^{-1} (all lakes)	0.08 mg L^{-1} (east) 0.06 mg L^{-1} (west)	Moderate	Low
Lake calcium	0.1-43.9 mg L^{-1}	1.20 mg L^{-1} (east) 1.65 mg L^{-1} (west)	Moderate	Low
Lake conductivity	2.2-341.8 μS cm^{-1}	9.8 μS cm^{-1} (east) 13.0 μS cm^{-1} (west)	High	Low
Fish Mercury	<0.01μg g^{-1}	0.03-0.09 μg g^{-1} (east) 0.04-1.10 μg g^{-1} (west)	High	High
Dieldrin	0.0 ng g^{-1} snow	>1.0 ng g^{-1} snow	High	High
DDT	0.0 ng g^{-1} fish	$\geq$4.0 ng g^{-1} fish	High	High



*Additional data sources: Western Airborne Contaminants Study (WACAP 2008).

Water: Extent and Connectivity of Wetland and Riparian Areas

What: Measures the extent and connectivity of riparian and wetlands* along the hydrologic network.

Why: To understand potential impacts on riparian and wetland communities as a result of hydrologic fragmentation due to human barriers (e.g., dams, ditches).

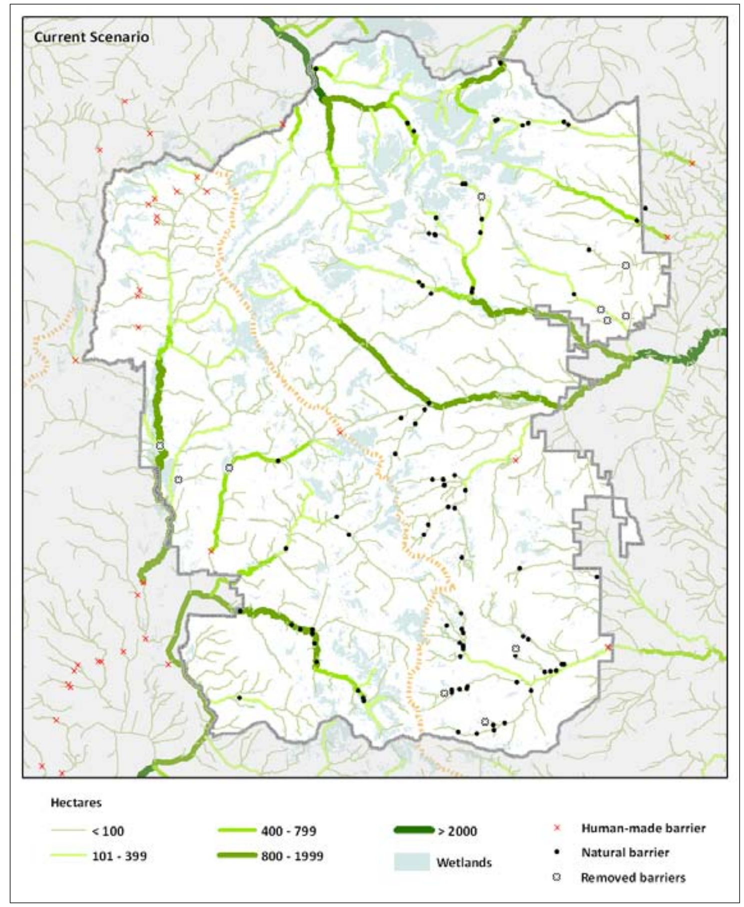
Stressors: Infrastructure, visitor use, climate change.

Confidence: High degree of concern; low evidence, moderate agreement.

Restoration of four dams and four ditches has improved the connectivity of riparian and wetland communities somewhat from 1900-1990s conditions, but current conditions (shown right) remain substantially fragmented compared to "natural" hydrological conditions.

Measure	"Natural"	Historic (1900-1990)	Current
Average connected stream length (km)	11.5 SD=36.5	8.7 SD=22.3	9.6 SD=26.2
Average connected riparian/wetland area (ha)	146.6 SD=410.2	112.1 SD=288.6	124.2 SD=322.6

*As mapped in ROMO vegetation map (Salas et al. 2005) and 1:24K hydrology.



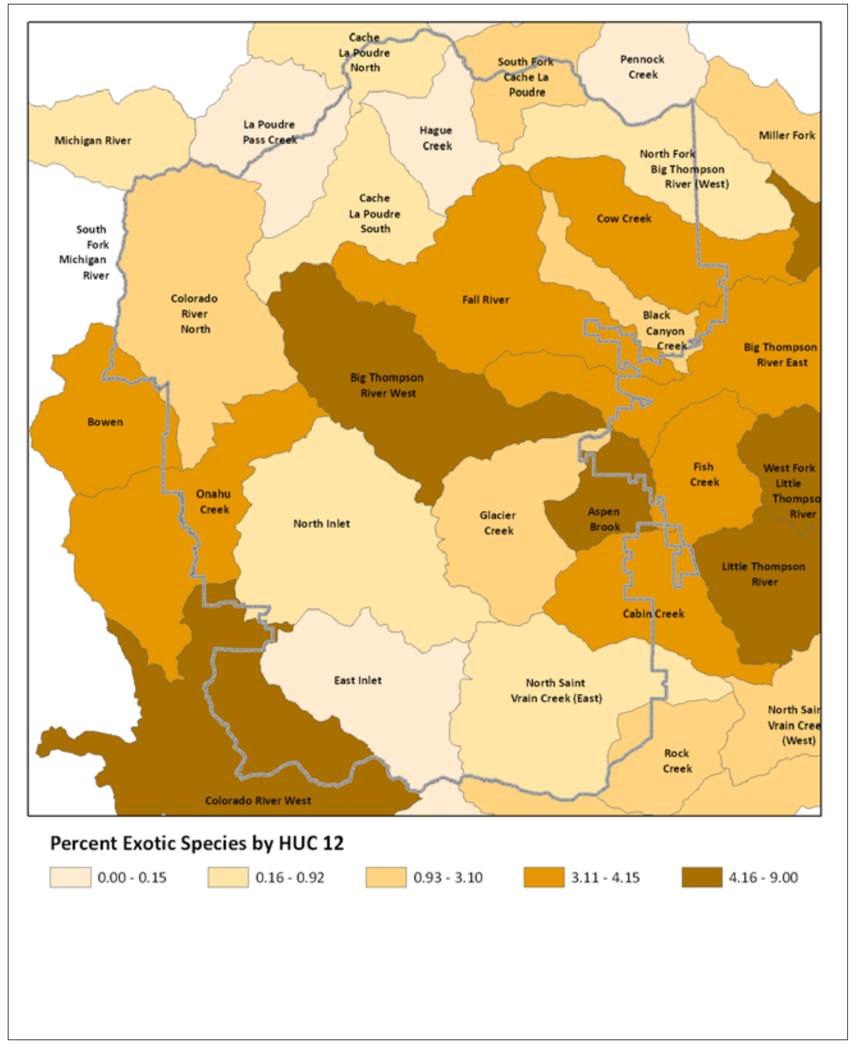
Biotic Integrity: Exotic Terrestrial Plant Species

What:	Measures the proportion and abundance of non-native, exotic plant species weighted by percent cover in each plot of the ROMO vegetation database (Salas et al. 2005).
Why:	Exotic species can displace native species, impact wildlife habitat by reducing forage and altering natural processes such as fire.
Stressors:	Visitor use, land use change, climate change.
Confidence:	High concern; moderate evidence, moderate agreement.

The distribution of known locations of exotic plants (especially cheatgrass) is strongly correlated with accessibility, with roughly 80% of known locations in highly accessible areas (<1 hour). East-side watersheds have higher rates of invasive species (2.8% vs. 1.8%), and lower montane and riparian ecological systems are particularly affected.

Measure	**Current condition**
Proportion of exotic species*	1.7% ROMO 4.6% outside ROMO
Proportion by ecological system*	
Alpine	0.1% (0.015 SE)
Upper montane	2.4% (0.036 SE)
Lower montane	5.2% (0.051 SE)
Riparian	4.6% (0.048 SE)
Savannah	1.5% (0.028 SE)

*Total of 1,861 plots: 1,279 within ROMO boundary, 571 outside of park.



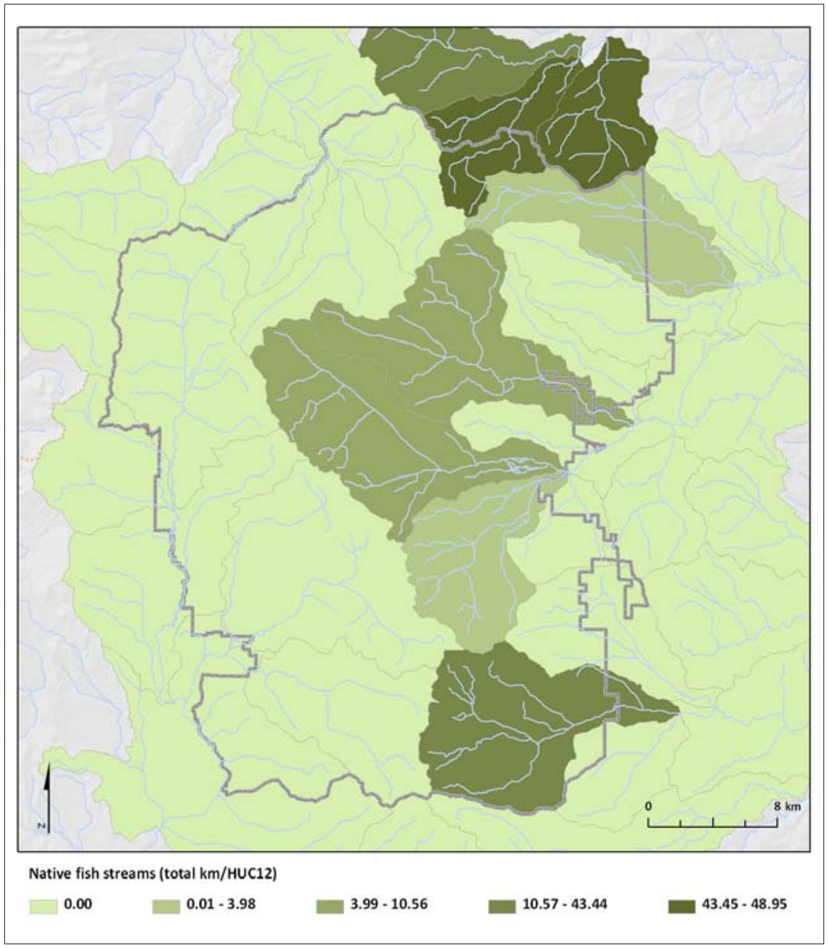
Biotic Integrity: Extent and Connectivity of Fish Distributions

What:	Measures the distribution of native and non-native fish, by incorporating observation data at streams and lakes with hydrologic connectivity (and barriers to up-stream movement).
Why:	Non-native species displace native species.
Stressors:	Riparian vegetation, visitor use, climate change.
Confidence:	High degree of concern; low evidence, moderate agreement.

Currently the proportion of streams that are “secure” (native only or fishless above a barrier) is 10% and there are 54 known human barriers, and native-only streams have increased slightly from 7.0% to 7.3% in the past 50 years.

Measure	Reference Condition	Current Condition
Proportion of streams with native-only fish	97.3%	7.3%
Proportion of streams with native fish	100%	75.8%
Proportion of streams* in ROMO above a barrier	100%	54%
Mean length of native-only fish streams (km)	228.5	76.1

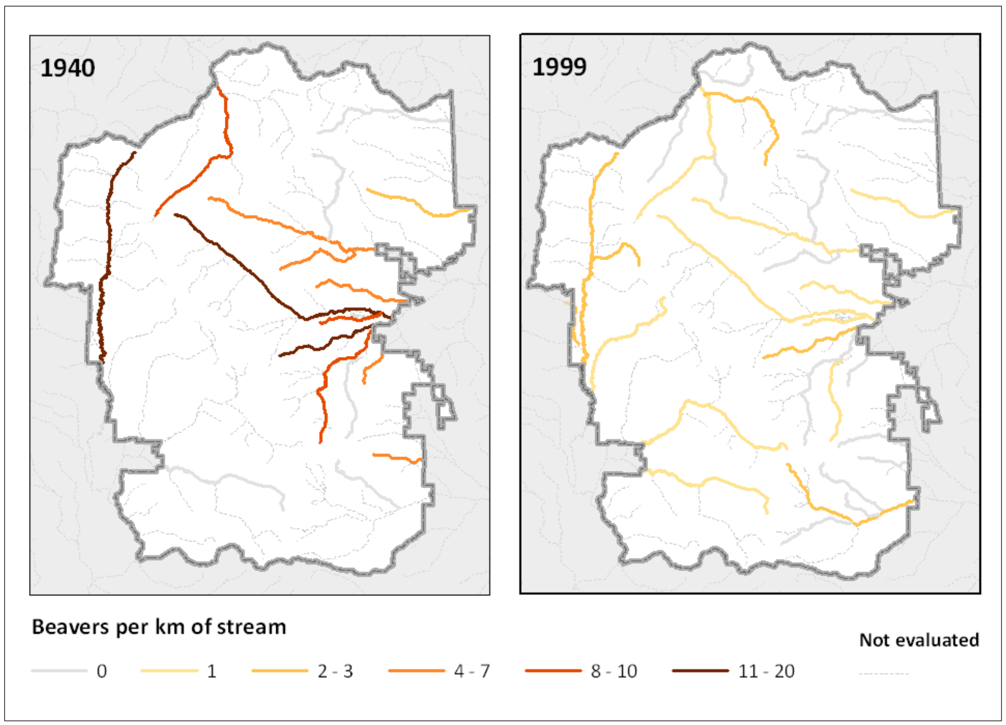
*Total length of streams in ROMO is 1,074.2 km (at 1:24K).

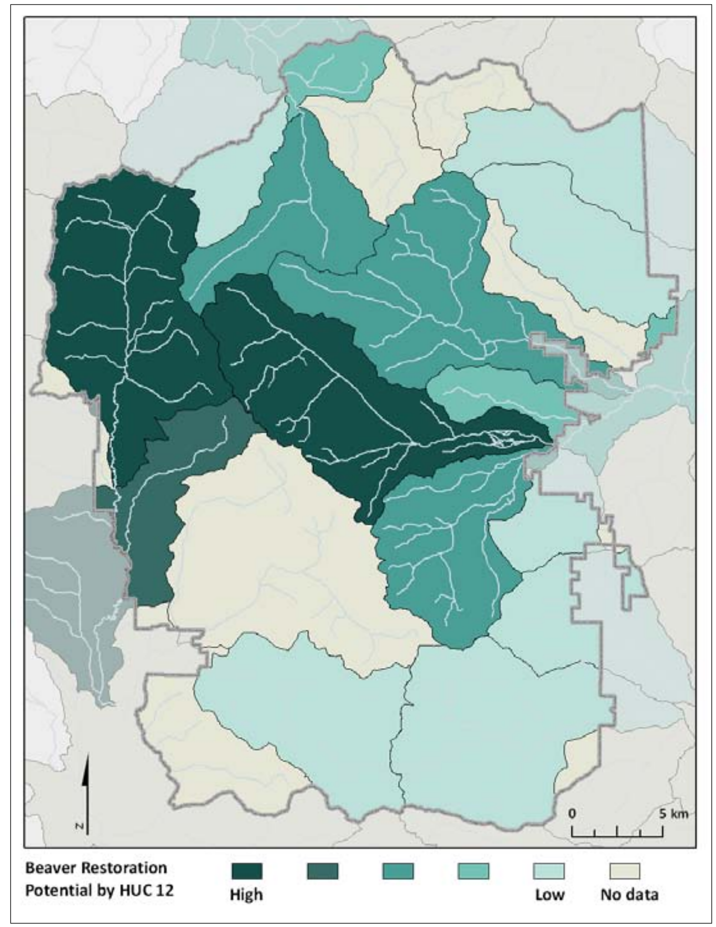


Biotic Integrity: Extent of Suitable Beaver Habitat

What:	Measures the distribution and proportion of potentially suitable beaver habitat and compares it to historical surveys.
Why:	Important to understand the historical role beaver had in riparian vegetation and is critical to understand elk/willow dynamics.
Stressors:	Over-abundance of elk, Grand Ditch, climate change.
Confidence:	High concern; moderate evidence, moderate agreement.

The current distribution of beaver is far below historic levels (bottom map). Highest areas for restoration potential (right map) include Colorado River (north); Big Thompson River (west), Onahu Creek, Cache la Poudre (south), Fall River, and Glacier Creek watersheds.





Landscapes: Extent and Pattern of Major Ecological Systems

What: Landscape metrics that characterize the extent and pattern of major terrestrial ecological systems using LANDFIRE existing vegetation types.

Why: These provide the landscape context of major ecological systems.

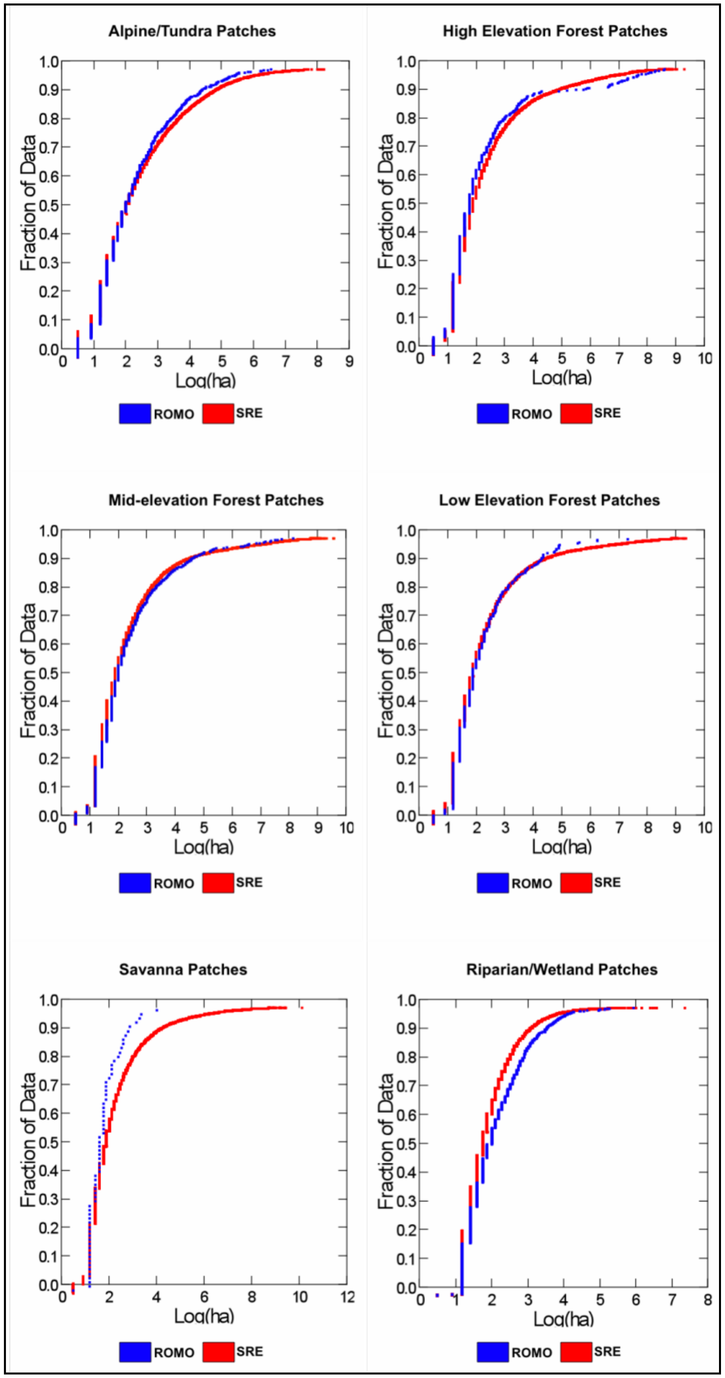
Stressors: Visitor use, land use change, climate change, exotics.

Confidence: Low degree of concern; low evidence, moderate agreement.

Generally the extent and pattern of patches within the park are similar to those found within the broader Southern Rockies Ecoregion (SRE), although there was some indication that the park contains more large patches of upper elevation forest, but smaller patches of alpine tundra, mid- and low-elevation forest.

Measure	Vegetation Type	Reference Condition (SRE)	Current Condition (ROMO)
Weighted mean patch size (ha)	Alpine tundra	654	180
	Upper elevation forest	1,868	2,600
	Mid-elevation forest	2,873	1,205
	Low-elevation forest	3,140	443
	Aspen	1,311	262
	Lodgepole	2,114	1,293
	Riparian/wetland	44	48
	Savannah	3,146	15

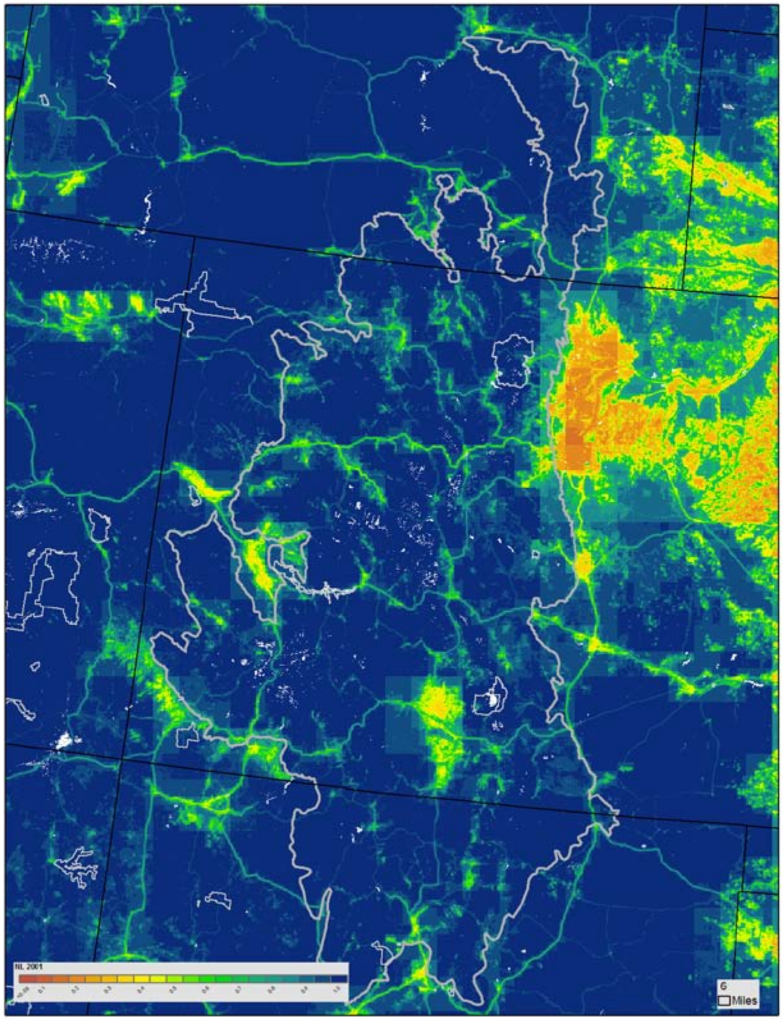
[1]Patches are defined by 12-digit HUC boundaries and contiguous (8 neighbor)



Landscapes: Connectivity of Natural Landscapes

What:	Measures the natural landscape context of ROMO within the Southern Rockies Ecoregion (SRE).
Why:	Movement of animals and ecological processes connect the park to adjacent landscapes beyond the park boundary.
Stressors:	Land use change, climate change.
Confidence:	High degree of concern; low evidence, moderate agreement.

Rocky Mountain National Park maintains natural landscapes that are placed within a key location to maintain connections to adjacent natural areas, especially to the north and west.



Time period	Natural Landscapes Metric Reference (SRE)	Natural Landscapes Metric ROMO
1992	0.931678	0.957785
2001	0.924163	0.955563
2030	0.916705	0.947110

* Data sources: NLCD retrofit product, SERGoM (Theobald 2005); National Transportation Atlas

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Prologue

Publisher's Note: This was one of several projects used to demonstrate a variety of study approaches and reporting products for a new series of natural resource condition assessments in national park units. Projects such as this one, undertaken during initial development phases for the new series, contributed to revised project standards and guidelines issued in 2009 and 2010 (applicable to projects started in 2009 or later years). Some or all of the work done for this project preceded those revisions. Consequently, aspects of this project's study approach and some report format and/or content details may not be consistent with the revised guidance, and may differ in comparison to what is found in more recently published reports from this series.

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Chapter 1. NRCA Background Information

1.1 NRCA Description

A natural resource condition assessment (NRCA) is a spatially explicit multi-disciplinary synthesis of existing scientific data and knowledge, from multiple sources, that helps answer the question: What are current conditions for important park natural resources? NRCAs strive to provide a mix of new insights and useful scientific documentation about current resource conditions and some of the factors influencing those conditions (i.e., issues and stressors). A successful NRCA has practical value to park managers for their ongoing efforts to:

1) develop near-term strategies and priorities (given limited park staff and funding, what are some park areas and resources deserving their greatest attention right now?);
2) engage in watershed or landscape scale resource partnerships and education efforts;
3) conduct formal planning to describe and quantify desired conditions for their most important resources, and to develop comprehensive strategies for how to best protect/restore those same resources; and
4) report to "resource condition status" performance/accountability measures as instructed by the Department of Interior and the Office of Management and Budget.

Typically NRCAs share standard elements related to study design and reporting products. Within those general sideboards many important study details remain flexible, to be decided on a park by park (individual project) basis. NRCAs *are multi-disciplinary (ecological) in scope*, though breadth and number of resources/indicators evaluated remains a project level decision; *report on current conditions across the entire park*, though for practical reasons some park areas will be excluded from consideration; *rely on existing data from NPS and other sources*, but field-based rapid assessment techniques can be used with prior approval; *use hierarchical study frameworks* that include the following components: natural resource indicators; reference conditions; current condition reporting by indicators, by ecological characteristics or attributes, and by park areas; *use the standard NRCA report outline* as the template to report key study findings; and *emphasize spatial analyses and reporting products* which are especially helpful for the primary types of expected uses (outlined above).

1.2 NRCA Purpose and Use

This document reports on an ecological assessment of natural resource conditions in and adjacent to Rocky Mountain National Park (ROMO)[1]. The broad project objective was to evaluate the conditions for a subset of important park natural resources—that is, a set of ecological attributes and resource condition indicators most relevant to ROMO. This is a broad, overview assessment

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[1] A companion assessment provides a report of conditions for Florissant Fossil Beds National Monument in Colorado and follows the general framework laid out in this report. The report citation is: Theobald, D.M., S.E. Linn, I. Leinwand, and J.B. Norman, III. 2010. *A Natural Resource Condition Assessment for Florissant Fossil Beds National Monument*. Natural Resource Report NPS/NRPC/WRD/NRR—2010/0XX. National Park Service, Fort Collins, Colorado.

that is comprehensive in scope and places the park within its regional context. It considers biotic and abiotic resources, and evaluates conditions for both aquatic and terrestrial components of the park. It identifies critical data and knowledge gaps, and provides a preliminary examination of the identified resources in the face of selected issues and stressors facing the park.

The report has relied on evaluation and synthesis of existing scientific data and information from multiple sources, combined with best professional judgment from an interdisciplinary team of specialists. To the extent possible, we have made use of quantitative data and analyses, but the report also recognizes the practical need to use expert opinion for many of the indicators—and reports on gaps in data and knowledge. We placed our assessment within an existing assessment framework to ensure a careful and explicit examination of the range of biotic and abiotic resources. The report emphasizes spatial analyses and products, including condition status for each indicator, some preliminary identification of pristine and "stressed" watersheds, and identification of most at-risk watersheds of the park. Although each indicator was developed independently based on the availability of relevant data, we summarize each indicator at a common scale—the HUC 12, or Hydrologic Unit Code, level 12—for consistency and comparability.

The three primary audiences for the assessment are: decision makers such as park superintendents, resource managers at the park, and scientists and technicians engaged to assist parks (e.g., Inventory & Monitoring Network ecologists and data managers). The assessment findings are designed to assist and inform these audiences for, among other things:

- Near-term strategic planning, to allocate limited staff and budget resources toward high priority (relatively more significant or vulnerable) park-managed watersheds and habitats;
- General Management Plan and Resource Stewardship Strategy development, which represent the planning process that formalizes park management zones, Desired Condition management objectives, and associated measurement indicators and targets;
- Park reporting to the Department of Interior's "land health goals" and to an Office of Management and Budget "resource condition scorecard";
- Park efforts to communicate and partner with other stakeholders, in order to address watershed- or landscape-scale resource management issues.

The specific objectives of this project were:

1. To provide park superintendents and managers with initial, science-based judgments about resource condition status, and to provide data, information, and recommendations that will be useful to park managers in their work to define the park's management zones and desired conditions.

2. To provide assessment statistics and summaries to allow park superintendents and managers to develop reports that meet GPRA and OMB reporting requirements.

3. To develop an assessment framework and process that can be repeated in the future and can serve as a template for resource assessments at other park units.

To address the project objectives, we conducted the study in three phases.

> Phase 1. We developed a scientifically-credible assessment and analytical framework for assessing and reporting on the current condition of resources within the park, and identied the principal near-term (~5-20 year) issues and stressors.
>
> Phase 2. We compiled a list of datasets and products that would be most pertinent and useful for assessing conditions within the park and that could reasonably be developed given the financial and time constraints of the project.
>
> Phase 3. We provided a multi-disciplinary assessment of resource condition to inform NPS about scientific significance, functional status, and current and emerging issues/challenges associated with park-managed resources and habitats. The assessment incorporates a strong geospatial component, uses a watershed framework to summarize and compare various indicators, and is presented as both a written report and a set of GIS databases.

Because the assessment is broad and integrative, a strong emphasis was placed on conducting spatially-explicit analyses using Geographic Information Systems (GIS) techniques. As a consequence, we developed numerous maps and visualizations of indicators and findings in this report, including a technical appendix, as well as a full suite of GIS datasets. We are planning to conduct a technical workshop for NPS staff on how to use and interpret the spatial datasets that we produced.

A main sign of success of this report will be the extent to which it provides park resource managers data and information that help them to see "the big picture" and relationships among critical issues, and to help place emerging issues within a local, regional, national, or global context.

Chapter 2. Park Resource Setting/Stewardship Context

2.1 Park Resource Setting

2.1.1 Description and Characterization of Park Natural Resources

This section provides a general discussion of the setting of Rocky Mountain National Park, including the regional and historic context, as well as unique and significant park resources and designations. This includes a number of reference maps on basic physiographic, biological, and cultural resources. The park, which straddles the Continental Divide, preserves some of the finest examples of physiographic, biologic, and scenic features of the southern Rocky Mountains. The park contains the headwaters of several river systems including the Colorado River. Geologic processes, including glaciation, have resulted in a varied and dramatic landscape. Elevations span from 7,630 feet to 14,259 feet—atop Longs Peak, a landmark feature. The park's varied elevations encompass diverse ecosystems where wilderness qualities dominate. Varied plant and animal communities and a variety of ecological processes prevail.

Threats from nutrient enrichment, eutrophication, sedimentation, invasive species, water and air pollution, and development on adjoining private lands are management concerns.

ROMO includes 14,259 foot Longs Peak which dominates the surrounding landscape. Trail Ridge Road, the highest continuous paved road in the nation, provides easy access to alpine tundra for many American and international visitors. Wildlife viewing, especially for elk during the fall rut, can be spectacular. Most of ROMO, just miles from the largest urban area in the Rocky Mountain region, is designated and/or managed as Wilderness, giving many Coloradans and other visitors an opportunity for solitude and wilderness recreation. Its complex topography and wide range of elevation result in a remarkable biological diversity.

ROMO's purpose and significant resources include its wild landscape and scenery, opportunities for solitude and tranquility, wilderness recreational and wildlife viewing opportunities, the scenic and scientific values of alpine tundra, and biodiversity (especially in three important ecosystems: tundra, forests, and aquatic and associated riparian systems). The park is a premier example of the southern Rocky Mountain region.

Important habitats include alpine tundra, montane habitats (especially ponderosa pine and upland shrub communities), lodgepole pine, riparian and wetland habitats, and aspen woodlands. Important species include elk, bighorn sheep, mule deer, mountain goat (exotic), moose (a recent arrival), beaver, black bear, wolverine (confirmed observation June 26, 2009), wolves (they may recolonize ROMO eventually), mountain lion (as an important large predator and a threat to human safety), pine marten, river otter, greenback cutthroat trout, Colorado River cutthroat trout, non-native fish (and other non-native aquatic species), boreal toad, raptors, white-tailed ptarmigan, songbirds, butterflies (there is extensive information on ROMO butterflies and evidence for their recent declines), capshell snail, exotic invasive plants, and rare plants.

Important ecological processes include fire, herbivory (especially by elk and moose) and its effects on aspen and willow communities, stream hydrology, other herbivores such as beaver and ptarmigan, exotic plant animal invasion, and erosion.

The following maps and tables provide general reference information about Rocky Mountain National Park (Figure 1 - Figure 8; Table 1 -Table 2).

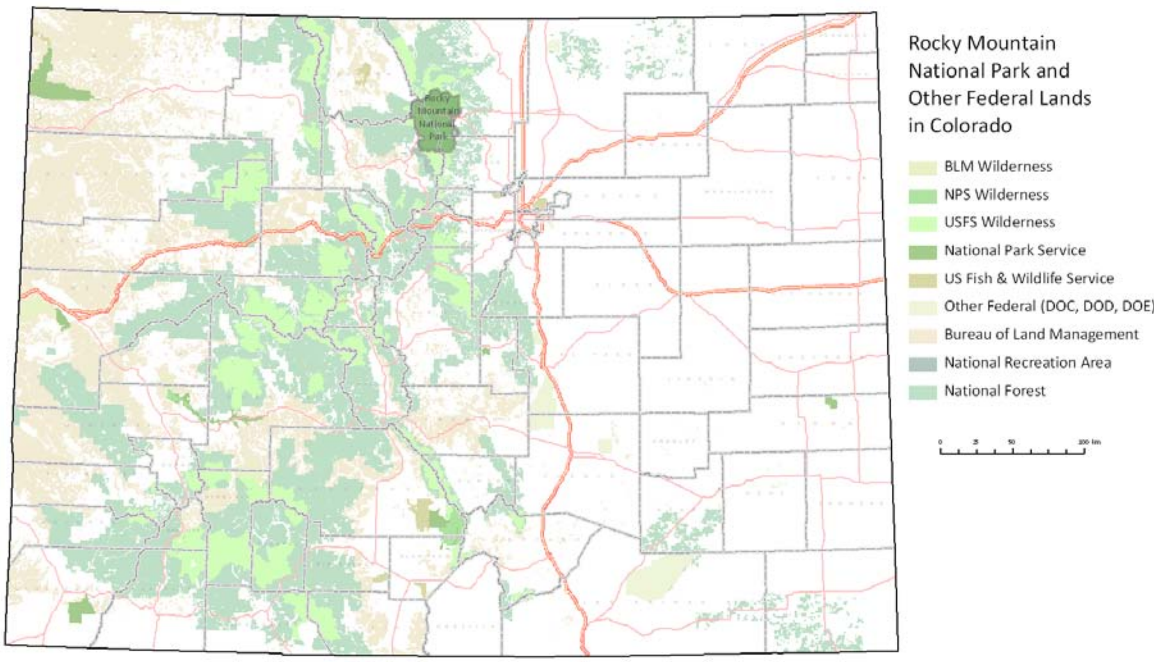


Figure 1. Rocky Mountain National Park and other federal lands in Colorado (Colorado Ownership, Management and Protection v7).

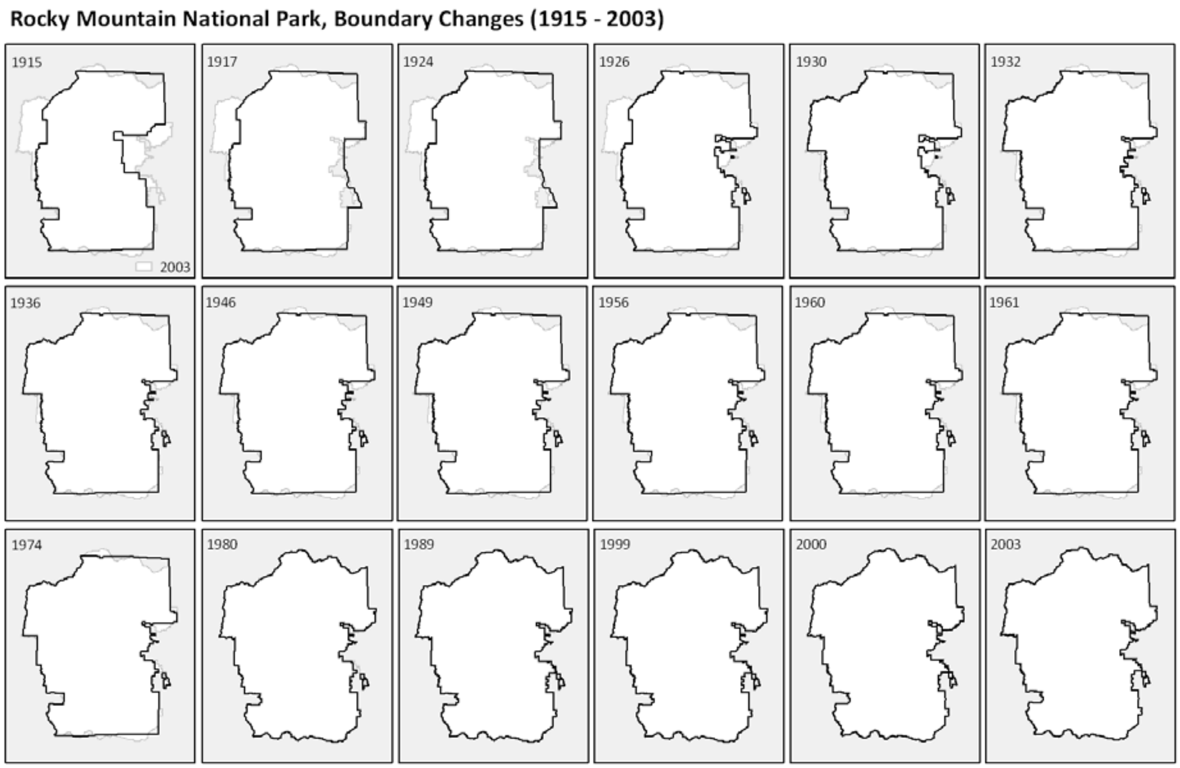


Figure 2. Boundary changes of Rocky Mountain National Park, 1915 – 2003. See [Animation.]

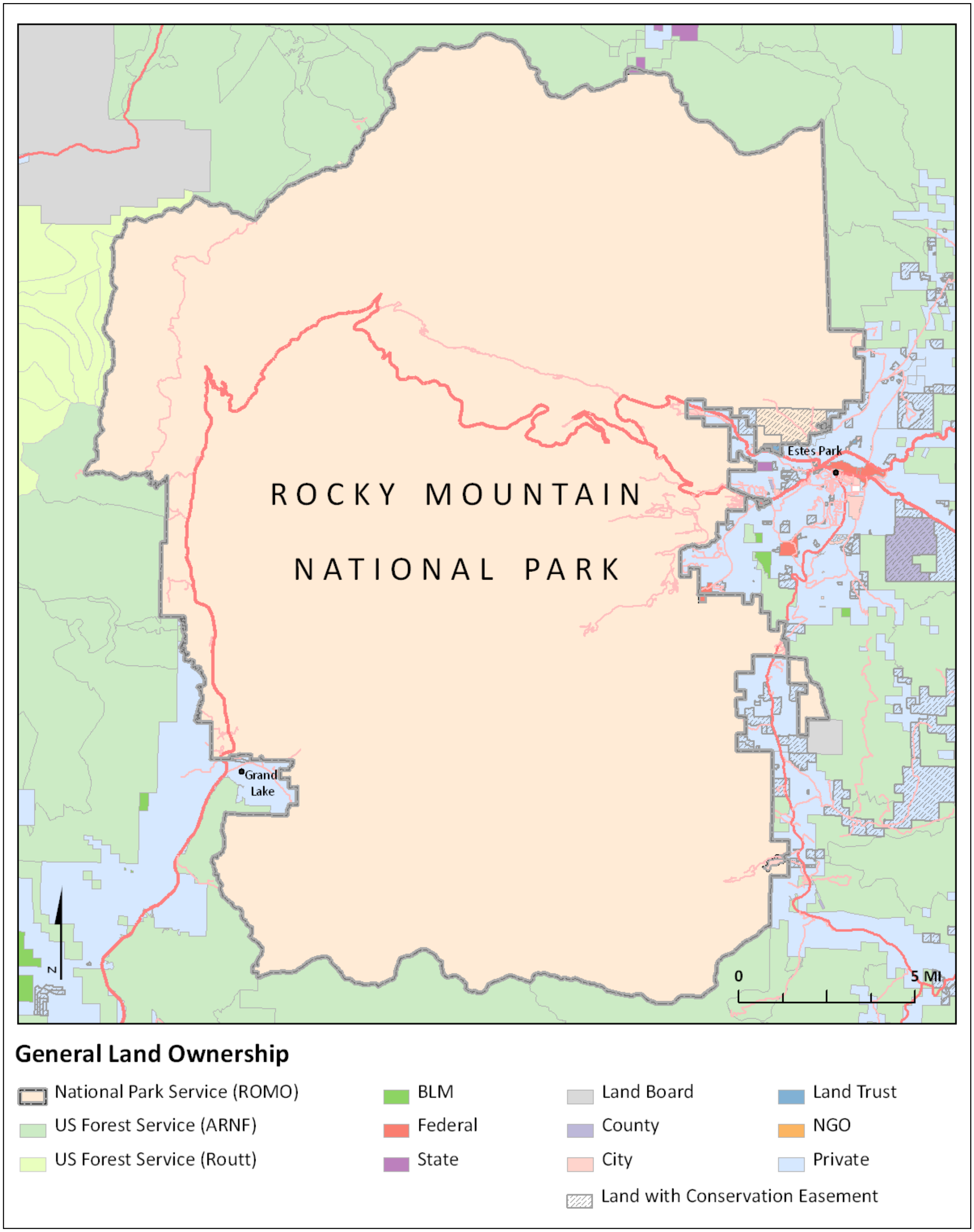


Figure 3. Major land ownership types around Rocky Mountain National Park in 2008. (Data source: Colorado Ownership Management and Protection v7, Theobald et al. 2008).

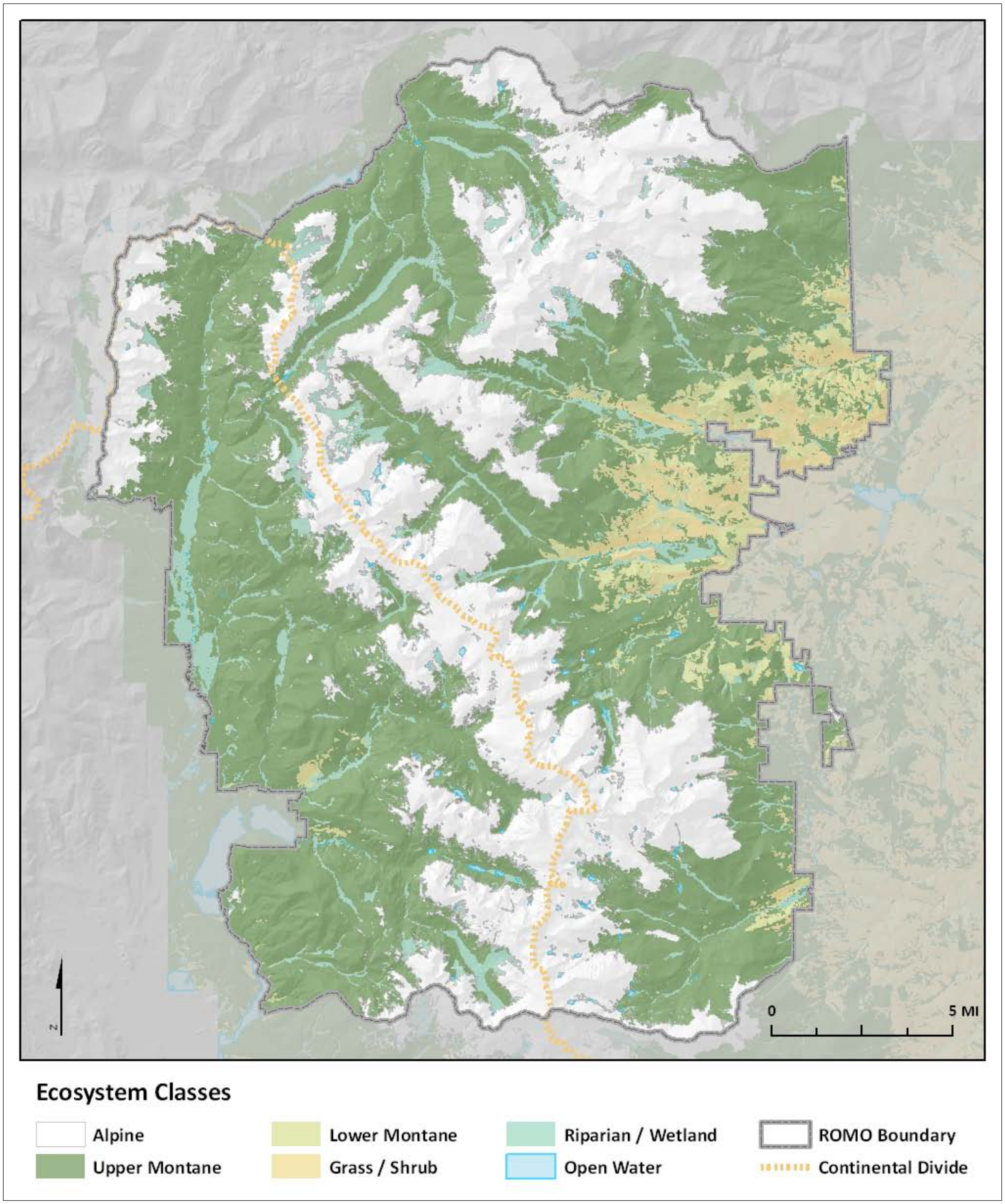


Figure 4. Six major ecosystem or "life-zone" classes generated from park-specific vegetation (Salas et al. 2005).

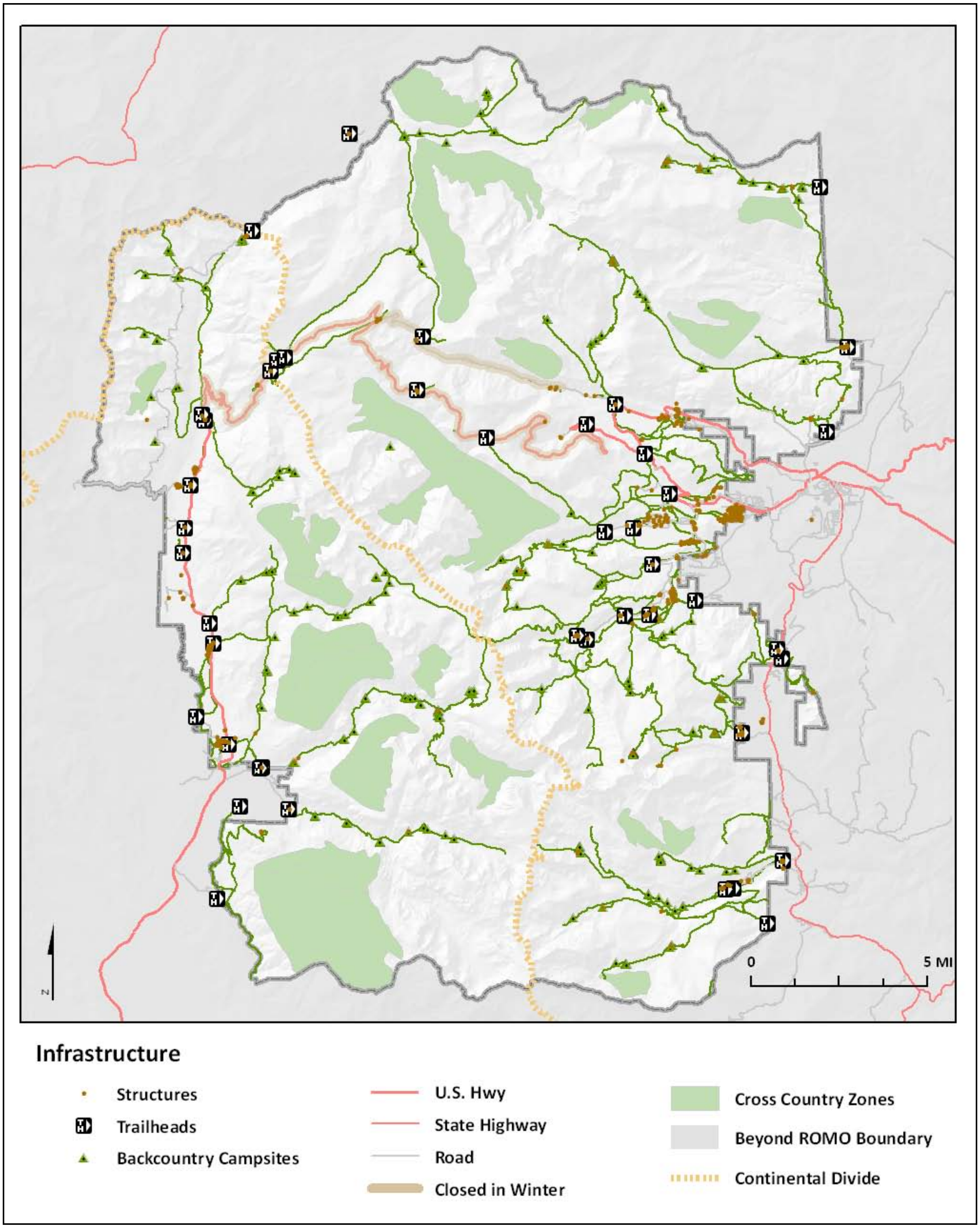


Figure 5. Roads and trails infrastructure inside ROMO. (Data source: http://www.nps.gov/gis/).

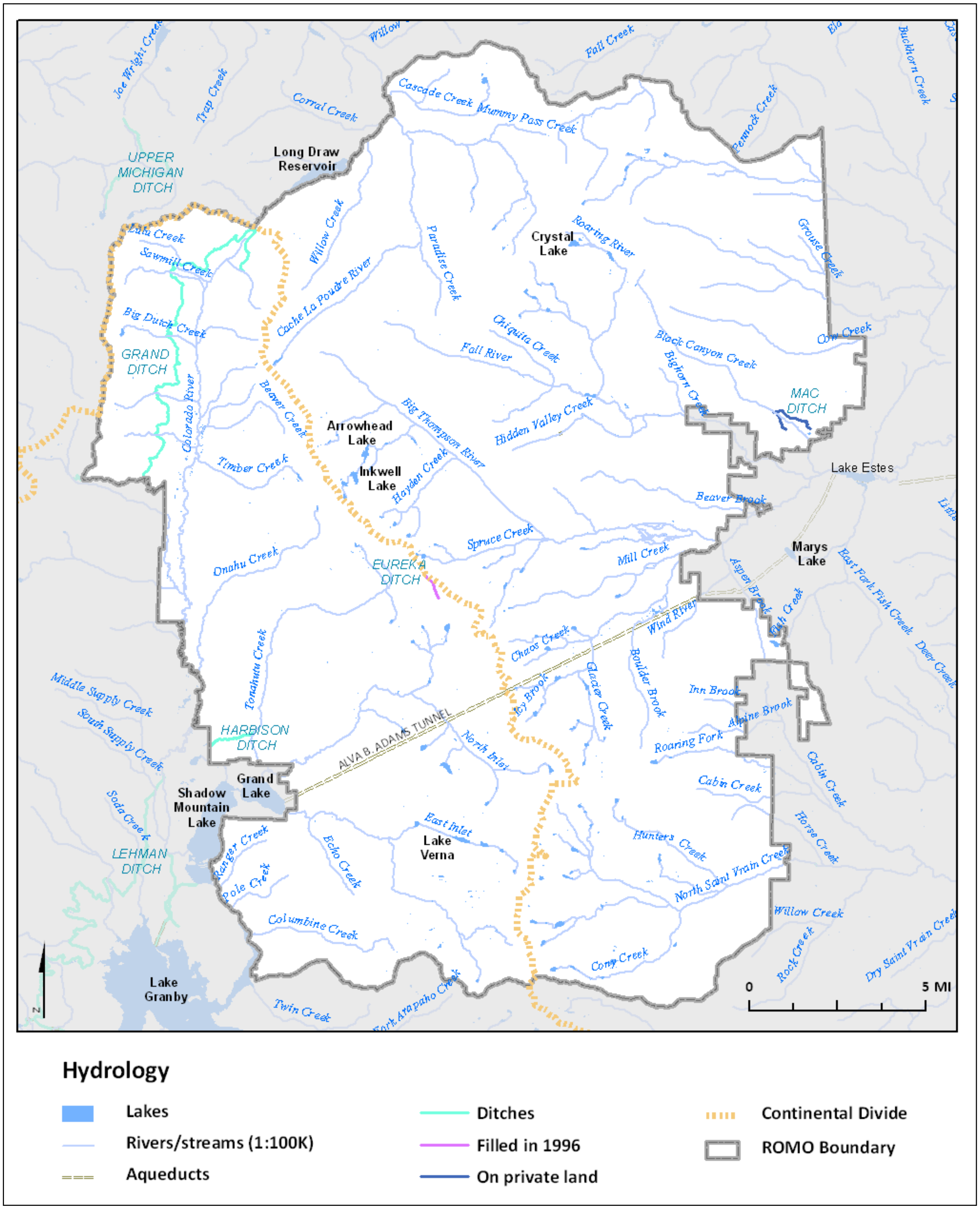


Figure 6. Major hydrologic features within ROMO. (Data source: National Hydrologic Dataset, 1:100K; http://www.nps.gov/gis/). Note that these data are for reference only; we used 1:24K scale maps for our indicator analyses below. Note that Eureka ditch was removed in 1996, Mac ditch still exists but is on private land.

Figure 7. Names of 12-digit Hydrologic Unit Codes (HUC-12 catchments) derived from the major tributary within each HUC-12 unit. Note 1:24K-scale hydrology shown.

Table 1. Catchment names associated with hydrologic 12-digit unit codes (HUC-12).

Hydrologic 12 digit unit code (HUC-12)	Catchment Name
101900060203	Aspen Brook
101900060207	Big Thompson River East
101900060202	Big Thompson River West
101900060205	Black Canyon Creek
140100010307	Buchanan Creek
101900050203	Cabin Creek
101900070205	Cache La Poudre North
101900070202	Cache La Poudre South
140100010302	Colorado River North
140100010308	Colorado River West
101900060101	Cow Creek
140100010304	East Inlet
101900060204	Fall River
101900060206	Fish Creek
101900060201	Glacier Creek
101900070203	La Poudre Pass Creek
101900060401	Little Thompson River
101800010503	Michigan River
101900050102	Middle Saint Vrain Creek
101900060103	Miller Fork
101900060104	North Fork Big Thompson (E)
101900060102	North Fork Big Thompson (W)
140100010305	North Inlet
101900050202	North Saint Vrain Creek (East)
101900050204	North Saint Vrain Creek (West)
140100010303	Onahu Creek
101900070103	Pennock Creek
101900050201	Rock Creek
101900070102	South Fork Cache La Poudre
101800010501	South Fork Michigan River
101900060402	West Fork Little Thompson River

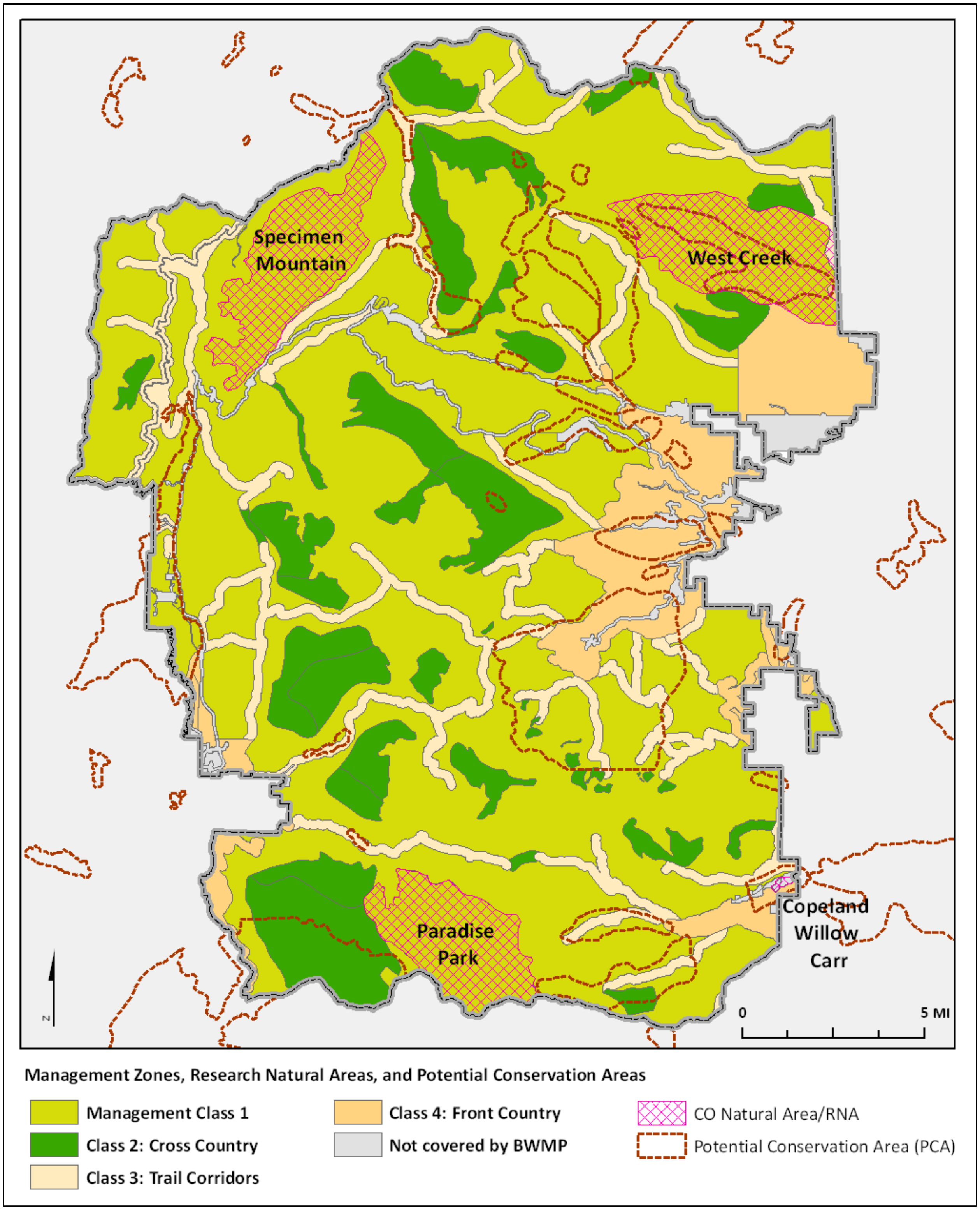


Figure 8. Management Zones found in ROMO as defined in the Backcountry/Wilderness Management Plan, 2001. Potential conservation areas are mapped by Colorado Natural Heritage Program. (Data source: http://www.nps.gov/gis/; CO State Parks).

Table 2. Definitions of management zones from Rocky Mountain National Park Backcountry/Wilderness Management Plan and Environmental Assessment (BWMP), 2001. Backcountry/Wilderness Management Plan, July 2001 (Chart contents were copied from metadata of *managezones2001.shp*).

	Management Class 1 Areas	**Class 2: Cross Country**	**Class 3: Trail Corridors**	**Class 4: Front Country**
	Approximately 170,236 acres, generally includes Research Natural Areas, tundra areas, and other areas not in Management Classes 2, 3 or 4.	*Approximately 36,832 acres, generally includes cross country routes, cross country camping areas, and bivouac areas*	*Approximately 27,474 acres, generally includes formal trail corridors (100 feet on either side of trail) and designated campsite areas (100 feet from edge of campsite)*	*Approximately 23,313 acres, generally includes formal trail corridors (200 feet on either side of trail), specific day use areas (200 feet from edge of area) and backcountry areas not recommended as Wilderness*
Use	• Day use only • No overnight camping (except approved management activities and winter area camping with restrictions) • Group size of seven (7) or less desirable • Low day use • No stock use	• Area camping allowed, seven (7) or fewer people; no fires • No designated camp areas (except Little Rock Lake) • Low to moderate use • No stock use	• Moderate - high • Day group size of no larger than 20 recommended • Designated campsites - group size 1-7 or 8-12 • Campfires in specific campsites only • Stock use allowed on stock designated trails and camp sites only	• High • No group size recommendation; however, large groups encouraged to split up • Day use only, no camping (except Moore Park, Rabbit Ears, Peregrine, Cub Lake, Arch Rocks, Mill Creek Basin and Upper Mill Creek designated camp areas) • Stock use allowed on stock designated trails only
Access and Challenge	• Generally moderate to difficult • Challenge/risk/freedom and self reliance are primary goals of the visitor	• Moderate to difficult • Challenge/risk/freedom and self reliance are primary goals of visitors	• Low to high • Broad spectrum of expected challenge level	• High access • Low to moderate challenge
Opportunity for solitude	• Outstanding opportunity for solitude • Chance of seeing other visitors/park staff is low • Natural sounds prevail	• Opportunity for solitude high most of the year, moderate during summer months • Chance of seeing other visitors/park staff is low to moderate • Some noise interferes with natural sounds	• Broad spectrum, low to high, depending on time of year, day of week, time of day, weather etc.	• Broad spectrum, low to moderate, depending on time of year, day of week, time of day, weather, etc. • Chance of seeing other visitors and staff high during summer months

	Management Class 1 Areas	Class 2: Cross Country	Class 3: Trail Corridors	Class 4: Front Country
Acceptable Resource Condition	• Natural environment with little evidence of recent impacts by humans • Evidence of management is extremely rare • Resource impacts are non-discernable	• Resource impacts are restricted to minor losses of vegetation where camping occurs and along use routes • Predominately unmodified natural environment	• Resource impacts are limited to the immediate trail corridor (100 feet either side of center line of trail) and campsites (100 foot radius from metal arrowhead)	• Resource impacts are limited to the immediate trail corridor (200 feet either side of center line of trail) and day use areas (200 foot radius from attraction)
Management Use	• No designated or maintained trails • Routes are generally non-discernable • No signs, cairns • No facilities • No aircraft or motorized equipment (except during emergency operations or absolutely critical for the protection of natural or cultural resources as determined on a case-by-case basis through a Minimum Requirement Analysis and approved by the Superintendent)	• No designated trails, but some designated routes • No formal maintained treadway (erosion and drainage control techniques allowed} • Minimum cairns as necessary to provide for resource protection and visitor safety • No facilities (cabins, hitchrails, privies) • No motorized equipment (except when approved via Minimum Requirement Analysis) • Only those signs necessary to protect resources and public safety	• Facilities: privies, hitchrails, corrals, cabins, tent pads, food protection devices, signs, research equipment etc. as per the Minimum Requirement Concept o Use of aircraft/motorized equipment/blasting, requires minimum Requirement Analysis (programmatically in an approved management plan or on an individual basis) • Use of stock for facility/trail maintenance • Designated, formally constructed and maintained trails (Standards D, E and F - see Section 2.1.4.7.2)	• Facilities: privies, hitchrails, signs, hardened areas at attractions etc. as per the Minimum Requirement Concept • Use of aircraft/motorized equipment/blasting, requires Minimum Requirement Analysis (programmatically in an approved management plan or on an individual basis) • Use of stock for facility/trail maintenance • Designated, formally

2.1.2 Overview of Resource Condition Issues

Important natural resource issues include visitor impacts (social trailing, crowding, back-country sanitation, trampling in alpine tundra, traffic and hiker effects on wildlife); aircraft overflights and impacts to wilderness values; adjacent land use development; air and water pollution (particulates and haze impacts to visibility and scenery, nitrogen deposition effects on terrestrial and aquatic systems, and mercury deposition); fire; erosion associated with failures of man-made irrigation ditches and impoundments; and over-abundance of elk.

2.2 Resource Stewardship Context

The following park designations set the legal and policy context for the park. The purpose, mission and significance statements are taken directly from park documents received from the manager of the ROMO park information office (personal correspondence, Katy Sykes, 2/23/09)

Rocky Mountain National Park (ROMO) was established by Act of Congress in 1915, and "is dedicated and set apart as a public park for the benefit and enjoyment of the people of the United States." (Jan. 26, 1915, Ch. 19, Sec. 1, 38 Stat. 798). The purpose of ROMO is to preserve the park's natural conditions and scenic beauties, its natural and historic objects and wildlife, and to provide the freest recreational uses consistent with this purpose. The National Park Service's mission at ROMO is to care for, protect, manage, improve, understand and interpret park resources and to provide for a high-quality visitor experience.

Rocky Mountain National Park provides exceptional accessibility to a wild landscape with dramatic scenery, opportunities for solitude and tranquility, wildlife viewing and a variety of recreational opportunities. The fragile alpine tundra encompasses one-third of the park and is one of the main scenic and scientific features for which the park was established. This is one of the largest examples of alpine tundra ecosystems preserved in the National Park System in the lower 48 states.

Chapter 3. Study Approach

3.1 Preliminary Scoping

There were three general steps in the process to conduct this assessment: forming an oversight team, holding a scoping workshop, and conducting the structured analyses (Figure 9).

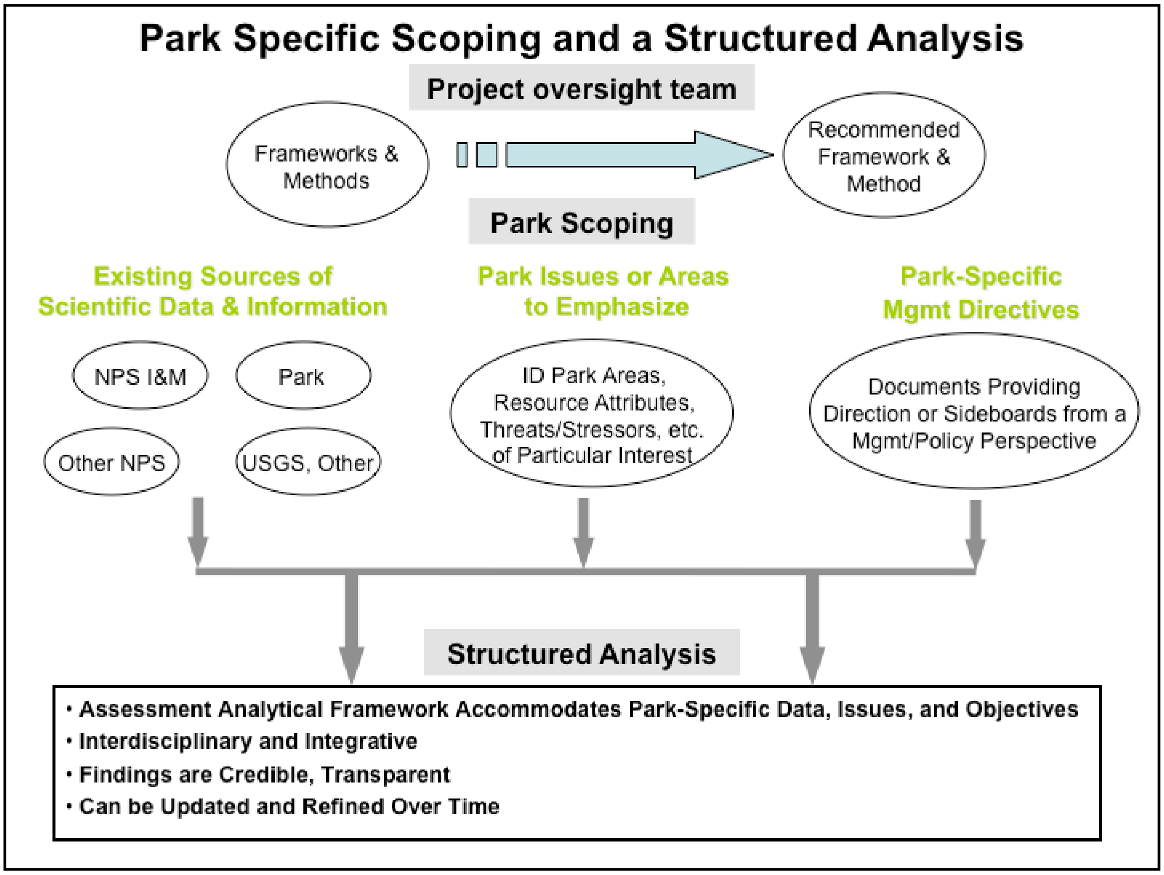


Figure 9. Diagram of park specific scoping and a structured analysis.

3.1.1 Advisory/Oversight Team

The first step in the process was to form a Project Advisory Team composed of scientists from Colorado State University and the National Park Service to provide general oversight to the project (Table 3). The charge of this team was to provide guidance on how to conduct the scoping workshop and provide general advice on the assessment.

Table 3. Members of the Project Advisory Team for the ROMO assessments. *Designates Technical Advisory role as well.

Individual	**Affiliation**	**Primary Area(s) of Expertise**
*David Theobald (lead P.I.)	Natural Resource Ecology Lab, Department of Human Dimensions, Colorado State University	Landscape ecology, terrestrial and freshwater spatial assessments, GIS.
Jill Baron (co-PI)	Natural Resource Ecology Lab, Colorado State University	Air and water quality; ecological indicators
Peter Newman (co-PI)	Department of Human Dimensions, Colorado State University	Visitor experience and standards and indicators
Barry Noon (co-PI)	Department of Fishery, Wildlife, and Conservation Biology, Colorado State University	T&E species, wildlife habitat
*John Norman	Natural Resource Ecology Lab, Colorado State University	GIS analysis, soil scientist
Jeff Albright (NPS Project Manager)	NPS-Water Resources Division	Hydrology, resource management
Mike Britten	NPS-I&M Rocky Mountain Network	Ecology
*Jeff Connor	NPS-Rocky Mountain National Park	Resource management
John Reber	NPS-IMR	Resource management
*Billy Schweiger	NPS-I&M Rocky Mountain Network	Ecology
Rick Wilson	NPS-Florissant Fossil Beds National Monument	Resource management

Members of the team met on a number of occasions to determine the process for developing and conducting the analysis (Table 4). Numerous smaller meetings and discussions were held but not summarized here.

Table 4. Summary of meetings with advisory team.

Task	Who	When/where
Formed *Advisory/Oversight Team*	CSU	
Field visit to parks	CSU, ROMN to ROMO, FLFO	ROMO FLFO: December 13, 2006
Advisory team meeting	CSU, ROMO, ROMN	
Scoping meeting	CSU, ROMO, FLFO, ROMN, IWR	December 18 - 19, 2006. ROMO visitor center
Update meetings		February 15 - 16, 2007
Technical workshops: FLoWS	CSU, ROMN	December 7, 2007
Synthesis meeting	w/technical team	December 16, 2008
GIS technical dissemination workshop	Technical team	May 2008

3.1.2 Scoping Workshop

The second step in our project was to hold a scoping workshop that engaged not only the investigators from CSU and the NPS staff who are members of the project oversight team (Table 3), but also NPS staff with management responsibilities at the park, and individuals from other agencies or groups that may be able to provide input on the availability of existing data or information sources.

The specific goals of the scoping workshop were to:

- briefly review the indicator framework and establish assessment goals at the park;
- elicit management issues faced by park managers;
- develop and *prioritize* a list of important indicators to inform assessment of ecological condition;
- identify data and information sources to generate indicators.

Because the Rocky Mountain Network (ROMN) had just released their draft report (Britten et al. 2007) and had developed a prioritized list of indicators for their vital signs that asked very similar questions, with many of the same people, we decided to "front-load" the scoping workshop by providing a preliminary listing of indicators that built on those identified in the Inventory and Monitoring (I&M) report as high-priority vital signs (Table 5). We believed that this would help to avoid developing yet another "laundry list" of indicators that was not comprehensive or potentially unbalanced. Note that we explicitly provided the opportunity at the workshop to nominate additional indicators not identified in the preliminary list.

Table 5. A listing of the Rocky Mountain Network high-priority vital signs (from Britten et al. 2007) used to "front-load" the discussion at the scoping workshop.

Table 3.3.6. Rocky Mountain Network high-priority vital signs.

National Level 1	National Level 2	National Level 3	ROMN final vital sign	FLFO	GLAC	GRKO	GRSA	LIBI	ROMO	Measures/Notes
Air and Climate	Air Quality	Wet and Dry Deposition	Wet and Dry Deposition	-	x	-	x	-	x	Includes deposition of nutrients and select other parameters; integrated with Weather and Climate, Wetland Communities, and aquatic vital signs.
Air and Climate	Weather and Climate	Weather and Climate	Weather and Climate	x	x	x	x	x	x	Includes core weather, snow distribution, and climate dynamics; integrated with nearly all other ROMN vital signs.
Water	Water Quality	Water Chemistry	Water Chemistry	x	x	x	x	-	x	Integrated into a holistic protocol with physical, chemical, and biological measures; emphasis on physical habitat, surficial hydrology, and benthos/periphyton assemblages; will be developed for both streams and select lakes.
Geology and Soils	Geomorphology	Stream/River Channel Characteristics	Surface Water Dynamics	x	x	x	x	?	x	
Water	Hydrology	Surface Water Dynamics		x	x	x	x	?	x	
Biological Integrity	Focal Species or Communities	Freshwater Communities	Freshwater Communities	x	x	x	x	-	x	
		Riparian communities		x	x	x	x	-	x	
Water	Water Quality	Aquatic Macroinvertebrates and Algae		x	x	x	x	-	x	
Biological Integrity	Invasive Species	Invasive/Exotic Animals	Invasive/Exotic Aquatic Biota	x	x	x	x	-	x	Integrated with Aquatic and Wetland Communities vital signs; detection modeling.
		Invasive/Exotic Plants		x	x	x	x	-	x	
Water	Hydrology	Groundwater Dynamics	Groundwater Dynamics	x	x	x	x	-	x	Integrated with Wetland Communities vital sign; select application to other systems.
Biological Integrity	Focal Species or Communities	Wetland Communities	Wetland Communities	x	x	x	x	-	x	Integrated into a holistic protocol with physical, chemical, and biological measures; emphasis on groundwater hydrology and vegetation.
Biological Integrity	Invasive Species	Invasive/Exotic Plants	Invasive/Exotic Plants	x	x	x	x	x	x	Integrated with Vegetation Composition, Structure, and Soils vital sign; detection modeling.

National Level 1	National Level 2	National Level 3	ROMN final vital sign	FLFO	GLAC	GRKO	GRSA	LIBI	ROMO	Notes
Biological Integrity	Focal Species or Communities	Sparsely Vegetated Communities (Alpine)	Vegetation Composition, Structure, and Soils	-	x	-	x	-	x	Integrated into a holistic protocol with emphasis on vegetation assemblage dynamics and soil quality in alpine and grasslan/shrublands.
Geology and Soils	Soil Quality	Soil Function and Dynamics (Alpine)		-	x	-	x	-	x	
Biological Integrity	Focal Species or Communities	Grassland Vegetation		x	?	x	?	x	?	
Geology and Soils	Soil Quality	Soil Function and Dynamics (Grasslands)		x	?	x	?	x	?	
Biological Integrity	Focal Species or Communities	Mammals Beaver	Focal Species–Beaver	x	x	-	x	-	x	Beaver vital sign will include landscape-scale assessment of habitat and presence/absence within the Stream and Wetland Ecological Integrity protocols. Elk and grizzly vital signs will include some landscape-scale habitat assessment and some elk herbivory measures in the Wetland Ecological Integrity and Grassland/Shrubland and Alpine Vegetation Composition, Strucutre, and Soils protocols. Elk and grizzly data from ongoing monitoring by the NPS, state agencies, and academics will also be used. GRSA Endemic Insect vital sign may include select population and habitat assessment.
		Mammals Elk	Focal Species–Elk	-	x	-	x	-	x	
		Mammals Grizzly Bear	Focal Species–Grizzly Bear	-	x	-	-	-	-	
		Insect Communities	Focal Species–GRSA Endemic Insects	-	-	-	x	-	-	
Landscapes (Ecosystem Pattern and Processes)	Landscape Dynamics	Land Cover and Use	Landscape Dynamics	x	x	x	x	x	x	Includes measures of land cover and use, spatial structure, and change detection; integrated with nearly all other ROMN vital signs.
	Soundscape	Viewscape/Dark Night Sky		x	x	x	x	x	x	

Dotted lines between records suggest areas where integration may lead to more efficient and meaningful assessment.

3.2 Reporting Areas

The ideal use of the findings of this report and the spatial datasets provided with the assessment is to inform and support park managers and scientists in developing recommendations about overall conditions in the park. That is, our intent is to provide a platform to assist ROMN and

ROMO scientists to make a judgment of resource condition through quick and ready access to data on important indicators. To do this, we summarized the ecological condition of ROMO as represented by the indicators for two reporting areas. First, we provide a general discussion and summary of each indicator by HUC-12 watershed. We also provide a well-documented summary dataset that can be used by park staff to further explore the comprehensive, summary dataset. Note that in addition to the raw value for each indicator for a given watershed, we also provide a normalized score. Our intent is to help provide a decision support system that facilitates park managers and scientists to explore the spatial pattern of high and low scores that reflect different incorporation of and weighting of different indicators. We also found it useful to summarize the condition indicators by *management zones* (outlined in Table 2).

3.3 Assessment Frameworks Used in the Study

In addition to forming the Advisory Team, the CSU investigators compiled existing approaches and conducted a brief literature review to identify a suite of different frameworks and approaches that have been developed and might be useful for the assessment. These existing approaches can be characterized generally as *ad hoc*, geomorphologic, or hierarchical (Table 6).

Table 6. Listing of existing assessment approaches reviewed for this study.

Type	Name	Citation
Ad hoc	*Ecosystem analysis at the watershed scale*	Federal Guide for Watershed Analysis 1995
	An ecological assessment of the U.S. Mid-Atlantic Region: A landscape atlas	Jones et al. 1997
	Natural habitat integrity	Tiner 2004
	CrEAM	White and Maurice 2004
Geomorphologic	Hydrogeomorphic	Hauer & Smith 1998
	Process domains	Montgomery 1999
Hierarchical	Hierarchical classification of drainage basins	Jensen et al. 2001
	A Framework for Assessing and Reporting on Ecological Condition	EPA 2002
	Watershed Analysis and Management Guide for States and Communities	EPA 2003
	Northwest Forest Plan - Preliminary assessment of the condition of watersheds	Reeves et al. 2004
	The Nature Conservancy's freshwater planning approach	Higgins et al. 2005
	Ecological Integrity Assessment & Performance Measures for Wetland Mitigation	NatureServe 2006

We held an initial Advisory Team meeting to review and evaluate potential assessment and threat analysis frameworks. Based on our preliminary literature review, we narrowed the list of candidate frameworks to the EPA's *A Framework for Assessing and Reporting on Ecological Condition – Essential Ecological Attributes (EEA); Ecosystem analysis at the watershed scale; Ecological Monitoring Framework (EMF); Northwest Forest Plan*; and the *Ecological Integrity Assessment & Performance Measures for Wetland Mitigation.* We selected the EPA's Essential Ecological Attribute (EEA) framework because it provides a useful checklist of EEAs, is comprehensive, has been used by others for watershed condition assessments so that we could benefit from their experience, distinguishes indicators of ecological condition as separate from stressors, and is flexible. We used it as a guide, but did not constrain discussion of resource condition by it (Figure 10).

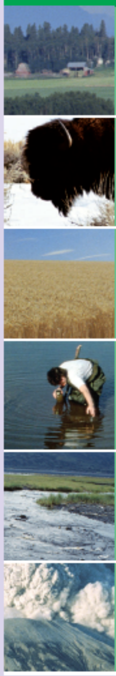


Exhibit 5-1: EPA Science Advisory Board essential ecological attributes

Essential Ecological Attribute	Description	Example Indicators
Landscape Condition	The extent, composition, and pattern of habitats in a landscape.	- Status and change in extent of ecosystems
Biotic Condition	The condition or viability of communities, populations, and individual biota.	- Imperiled species in the U.S. - At-risk native species - Trends in invasive and non-invasive birds in grasslands and shrublands
Ecological Processes	Metabolic function of ecosystems - energy flow, element cycling, and the production, consumption, and decomposition of organic matter.	- Primary productivity - Movement of nitrogen
Chemical and Physical Characteristics	Physical parameters (e.g., temperature) and concentrations of chemical substances (e.g., nitrogen) present in the environment.	- Nitrate, phosphate, and other chemical levels in streams
Hydrology and Geomorphology	The interplay of water flow and land forms.	- Soil erosion - Change in stream flow rates
Natural Disturbance Regimes	The historical function of discrete and recurrent disturbances that shape ecosystems.	- Forest disturbances: fire, insects, and disease

Source: EPA, Science Advisory Board. *Framework for Assessing and Reporting on Ecological Condition.* June 2002.

Figure 10. The top level of the Essential Ecological Attribute hierarchy (USEPA, 2002)

We used the Ecological Monitoring Framework (EMF) as the framework for our assessment indicators (Fancy et al. 2009). The EMF was developed to organize and promote a systems-based approach to monitoring, and itself is based on a variety of frameworks, including the EPA's Essential Ecological Attributes (EPA 2002). Organizing the assessment indicators into this framework helps ensure complementarity and provides a direct coupling with the NPS' Inventory & Monitoring program (Table 7).

For each indicator we collected data and conducted a separate analysis. Because the amount, quality, and geographic coverage of data and knowledge about each indicator ranged considerably, the approach to developing each indicator was unique. Rather than limiting any one particular indicator to adhere to some minimum level of data or consistent approach, we decided to allow the analysis of each indicator to be pursued somewhat independently. To provide a means to examine the distribution of values of an indicator for specific parts of the park, as well as to provide a tool for park staff to investigate combinations of indicators by geographic location, we generated a summary database that contains both the raw values and condition values for each 12-digit HUC watershed. This approach ensures that each indicator is referenced to a common theme—that is, the map of ROMO—because the ability to spatially reference indicator values is essential for a management response. Because of the limited resources available for this project, we focused on assessing landscape patterns, dynamics, and structure as derived from existing land cover data and other existing geospatial datasets, rather than conducting new site-specific analyses.

Table 7. List of indicators identified during scoping workshop, organized by NPS Inventory & Monitoring Ecological Monitoring Framework.

NPS Level 1 Vital Sign	Indicators	Decision Maker Questions and Issues
Air & Climate	Condition of alpine lakes	How does water quality of park lakes compare to other lakes?
	Wet and dry atmospheric deposition	What are trends in deposition of pollutants to the park?
Water	Monthly & annual discharge in streams	How do diversions and the Grand Ditch affect wetland areas?
Biotic Integrity	Extent of invasive terrestrial plants	Where are areas with low occurrence of exotics to monitor?
	Extent and proportion of non-native fish	Where are refugia? Where are re-introductions most likely to be successful?
	Extent of potentially suitable beaver habitat	How many beaver could ROMO support? Where would their habitat be? How is that important for elk/willow dynamics?
	Extent of major stream, lake, wetland and riparian types	Where are most important riparian/wetland areas? How connected are they to the stream network?
	Connectivity/isolation of freshwater system types	Where are the most important riparian/wetland areas? How connected are they to the stream system?
Landscapes	Disturbance-dependent vegetation and seral/successional state	Where are forest fuels? Which watersheds are most susceptible to insect/fire/erosion cycle?
	Major ecological systems	Are Research Natural Areas useful for reference condition?
	Land use change	What are trends, rates, and patterns of land use change surrounding parks (ROMO, FLFO)? What is the affect of WUI–related treatments on other park resources?
	Landscape connectivity	How are changes in habitat and connectivity related to bighorn sheep? Possible introduction of wolves? Role of park for lynx?

Note that early in our project we began to pursue developing a simple conceptual model for each indicator. A conceptual model

> "…outlines the interconnections among ecosystem components, the strength, and direction of those linkages, and the attributes that characterize the state of the system. The model should demonstrate how the system "works," with particular emphasis on anticipated system responses to human-induced stresses. The model should also indicate the pathways by which the system accommodates natural disturbances and what system attributes provide resilience to disturbance. These processes could be portrayed by illustrating the acceptable bounds of variation of system components, and normal patterns of variation in input and output among the model elements" (Noon & McKelvey 2006: 946).

After attempting to work through a couple indicators, it was clear that there were insufficient project resources to complete this task in a reasonable way, although we believe that ultimately deeper understanding and communication of these indicators to managers and the public is best founded on explicit representation of the system in the form of conceptual models. Some useful resources are available on communication with conceptual models (Heemskerk et al. 2003) and a primer for developing conceptual models (Gross 2003).

Table 8 provides a finalized list of the indicators and anticipated questions and issues that each indicator is intended to address. Note that the indicators listed here are a slight re-organization of the list of indicators from the scoping workshop included in Table 7. We made these modifications to better reflect changes (subsequent to the workshop) to the EMF and further discussions among the PIs.

Table 8. The final list of indicators selected for the assessment, paired with anticipated questions and issues of decision makers that each indicator is intended to address.

NPS Level 1 Vital Sign	Indicators	Decision Maker Questions & Issues
Air & Climate	Condition of alpine lakes and atmospheric deposition	How does water quality of select park lakes compare to other lakes? What are trends in deposition of pollutants to park?
Water	Extent and connectivity of wetland and riparian areas	Where are most important riparian/wetland areas? How connected are they to stream systems?
Biotic Integrity	Extent of exotic terrestrial plants	Where are exotic plant species located? Where are areas with low occurrence of exotics that should be monitored?
	Extent of fish distributions	Where are refugia? Where are re-introductions most likely to be successful?
	Extent of suitable beaver habitat	How many beaver could ROMO support? Where would their habitat be and what is their importance for elk/willow dynamics?
Landscapes	Extent and pattern of major ecological systems	Are RNAs useful for reference condition? Where are forest fuels? Which watersheds are most susceptible to insect/fire/erosion cycle?
	Natural landscapes and connectivity	How are ranges in habitat and connectivity related to bighorn sheep? Possible introduction of wolves? Role of park for lynx?

3.4 Reference Condition Framework

Here we distinguish an assessment from a more general characterization study. An *assessment* attempts to measure condition relative to some benchmark; it is placed within a context of expected or desired conditions that are described by a set of reference distributions.

Ecosystems are complex and multidimensional, yet their management and measurement require simplification to a small number of indicator variables. An *ecological indicator* is any measurable attribute that provides insights into the state of the environment and provides information beyond its own measurement (Noon 2003). Indicators are usually surrogates for properties or system responses that are too difficult or costly to measure directly (Leibowitz et al. 1999). Indicators differ from estimators in that functional relationships between the indicator and the various ecological attributes are generally unknown (McKelvey and Pearson 2001). Not all indicators are equally informative—one of the key challenges to assessment and monitoring is to select for measurement those attributes whose values (or trends) provide insights into ecological integrity at the scale of the ecosystem. In developing the list of indicators and specific measures, we considered some basic criteria for useful ecological indicators as provided by Harwell et al. (1999). Useful indicators need to be understandable to multiple audiences, including scientists, policy makers, managers and the public; they need to show status and/or condition over time; and there should be a clear, transparent scientific basis for the assigned condition.

An essential component of an assessment or monitoring program is the generation of expected values (e.g., baselines) or expected time trends of the ecological indicators. Only by comparing observed with expected values or trends can a determination be made about the current state of the ecosystem or the effectiveness of management practices. The close approach to, or the passing of, an expected value is the threshold point that triggers a change in management practices. In the ecological literature, these expected values have been referred to as *reference conditions*—"the condition in the absence of human disturbance which is used to describe the standard, or benchmark, against which the current condition is compared" (Sanchez-Montoya et al. 2009:41). It is often difficult, however, to standardize reference conditions across indicators. This is because different ecosystem indicators vary in the degree to which they reflect a pristine state. Some ecosystem types are more degraded than others. Stoddard et al. (2006) have usefully categorized reference conditions along a continuum from minimally disturbed, to historical condition, to least disturbed, to best attainable. Reference conditions are also subtly different from desired future conditions, which are typically a simple narrative statement. In a world dominated by human behavior, reference conditions may reflect what is realistically attainable, not necessarily is what is desirable. We also caution that benchmarks are needed for monitoring programs even though "steady-state" and "the balance of nature" are antiquated paradigms.

Estimating reference conditions is difficult, and imprecise for several reasons: (1) the limited availability of pristine, undisturbed ecosystems to provide insights to benchmark conditions; (2) an incomplete understanding of the relationship between the value of an indicator and the desired ecosystem state(s); (3) inadequate knowledge of the expected variability, over time and space, of the indicator of ecosystem state (or species status); (4) the non-linear relationships between indicator values and ecosystem processes, including the existence of sharp threshold regions – so called "ecological thresholds" (Groffman et al. 2006); and (5) the fact that indicator benchmarks may be best represented by probability distributions rather than single target values (Noon 2003).

Expected values and thresholds as discrete targets implicitly assume that an ecosystem will evolve to (or was historically at) a dynamic steady state with regard to its structure, composition, and processes. This assumption is often false. The dynamic nature of ecosystems argues for specifying a distribution of indicator values rather than an expected value at a single point in time or space. That is, the state(s) of an ecosystem is best described by a probability distribution rather than a specific target value. In practice, this makes the management decision process less certain, but the probability concept is a more realistic characterization of nature. The challenge to the manager is two-fold—to assess the state of the system, and to determine if the current state is under an improbable natural disturbance regime. If the system is degraded, or in an improbable state, some management response is triggered.

Determining threshold values and reference distributions (Stoddard et al. 2006) first requires the selection of both a spatial and temporal scale to observe the ecosystem. If the spatial scale is a point in space—for example, when measuring stream temperature at a single location—an indicator threshold may be specified as a single value. However, if the spatial scale includes entire parks, complete watershed(s), or the geographic range of a species, specifying an expected distribution of indicator values over the area would be more appropriate. Thus, there are two different categories of indicators—those that lend themselves to threshold values at local temporal and spatial scales (e.g., water temperature for some fish and amphibians), and those best categorized by a reference distribution (e.g., mean and variance of the number of snags per hectare). In practice, few indicators will be characterized by a single target value. Because the physical and biological processes and structural/compositional elements that characterize ecosystems vary in space and time, most indicators are best considered random variables. That is, when integrated across space (time), at a given point in time (space), a specific process or landscape element is characterized by a dynamic reference distribution. This distribution, often referred to as the historic (or natural) range of variation (Landres et al. 1999; Parson et al. 1999), is critically dependent on the spatial scale and temporal window over which the distribution is estimated.

Once the scale of observation has been determined, it is possible to aggregate indicator values into a frequency distribution. The observed distribution of indicator values would then be compared to the expected distribution to detect both the magnitude and pattern of deviation from desired conditions. The concept of a spatial distribution of indicator values as the appropriate evaluative statistic is critical to the monitoring and assessment of ecological systems (Figure 11; Stoddard et al. 2006).

A useful assessment and monitoring program must address two distinct questions: (1) Is the observed value of the indicator at a specific location at a specific time within acceptable bounds of the expected probability distribution?; and (2) When indicator values are combined, across space or time, does the expected distribution of indicator values result?

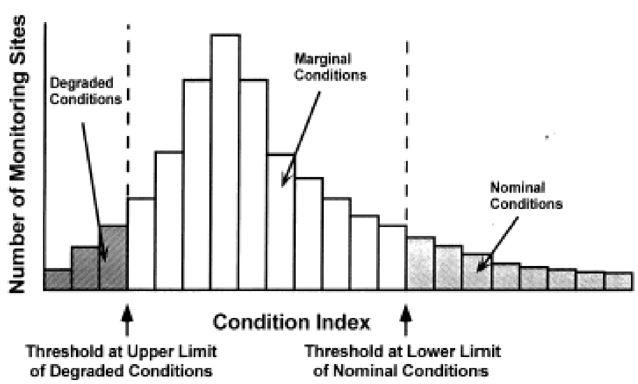


Figure 11. Distribution of indicator values based on sampling numerous sites at various locations on the landscape. Individual sites can be interpreted as representing degraded, marginal, or nominal ecological conditions, but the overall inference is to the ecological state at a landscape scale (from Noon 2003).

For a given resource on the landscape (e.g., a segment of stream, a forest stand, a riparian corridor), it may be appropriate to establish a target value for a given indicator. However, when evaluating deviation from the desired ecosystem state at the landscape scale, inferences drawn from the indicator's value at a site are of limited use without considering that signal in the broader context of values from neighboring landscape locations. A useful way to portray the distribution data is as a cumulative frequency distribution, which allows an estimate of the proportion of the sample locations below a certain indicator score (Figure 12).

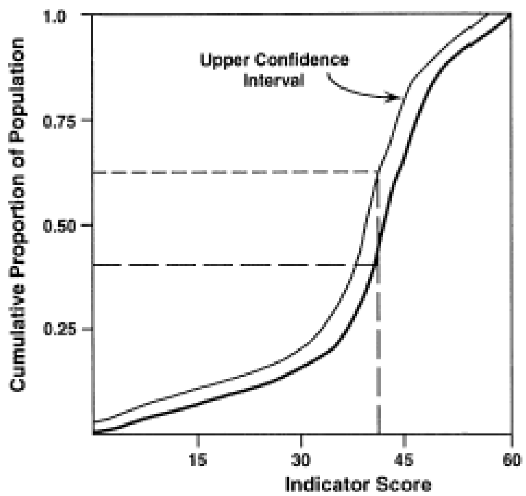


Figure 12. Cumulative distribution of indicator scores based on sampling numerous sites at various locations on the landscape. The proportion of sites below a certain indicator score can be readily inferred (from EPA 1993).

Despite the importance of establishing benchmark distributions, the process of establishing reference conditions is subject to some degree of arbitrariness. For example, there is uncertainty on how benchmark conditions are to be estimated (Stoddard et al. 2006). There is no clear guidance on how far back in time, or to what spatial extent, one should go to find an appropriate point of reference or what constitutes pristine conditions. There may be no current analogs for past conditions. In addition, it is clear that the concept of benchmarks can be reconciled with the dynamical nature of ecosystems only in terms of frequency distributions, especially when viewed over long temporal or broad spatial scales. Thus, all decisions about the proximity of an indicator to its expected value must be made in probabilistic terms.

The process of developing reference conditions as expected distributions for assessment or monitoring requires two key questions to be addressed: (1) What set of environmental features (i.e., indicators) should be selected to best characterize the state of an ecosystem?; and (2) What temporal and spatial scales should be assumed for estimating the historic range of variations or benchmark conditions? One useful distinction for indicators is based on scale and discriminates among so-called "coarse-filter" and "fine-filter" measures of ecosystems. Coarse-filter measures include, for example, assessments based on the area and spatial distribution of dominant vegetation types and their successional stages at the scale of large watersheds. Fine-filter measures could include vegetation elements such as downed wood and snags, and population measures for individual plant or animal species.

An exhaustive set of coarse- and fine-filter indicators should possess the properties of complementarity and comprehensiveness (Noon 2003; Noon and McKelvey 2006). Individual indicators should be minimally redundant and provide insights that complement other measurements. Collectively, a set of non-redundant measures should span the temporal and spatial dimensions that characterize an ecosystem. These properties are difficult to achieve in a minimal indicator set but are useful goals to strive for. Given the complexity and dimensionality of an ecosystem, a surrogate-based approach to ecosystem assessment is a pragmatic requirement. The challenge is in the selection of the set of indicators—the collection of indicators that, collectively, have the properties of complementarity and comprehensiveness (Noon and McKelvey 2006). Indicators are complementary if their information content is largely independent of other indicators, and the set of indicators is comprehensive if they collectively span the full dimensionality of the ecosystem. Pragmatic considerations alone dictate that only a small number of indicators can possibly be measured. However, strategies and processes for selecting ecological indicators are complex and poorly developed (Barber 1994, NRC 1995).

We have provided this discussion of ecological indicators and reference condition as a "best practices" for assessments. However, we recognize that because of limitations of data, knowledge, and resources (time and money), we were forced to take practical, first steps in this assessment. That is, our estimation of reference condition for our indicators presented here were based primarily on best professional judgment and data available, not based on more rigorous approaches discussed above. We pursued these simplified approaches because of practical limitations, but we placed our work explicitly into this broader reference condition framework and encourage more conceptually grounded and rigorous assessments in the future.

A reference condition describes

> "… a distribution rather than a single absolute value. The range of values (for any given index or metric) results from sampling error and natural variability, both in time and in space. It is the degree of spatial or temporal variance, removed from sampling error, that is of interest. At any point in time, a set of sites, all in undisturbed condition, will exhibit a range of biological attributes. In addition, single sites in a natural state will vary over time, due to the influences of climate and natural disturbance" (Stoddard et al. 2006: 1269).

The specific terms used to characterize the reference condition to which current conditions are compared are (Stoddard et al. 2006):

- "minimally disturbed condition" (MDC);
- "historical condition" (HC);
- "least disturbed condition" (LDC); and
- "best attainable condition" (BAC).

For each indicator in this assessment, a reference condition was determined using the most rigorous means possible. However, limited availability of data, research or historic accounts prevented a high level of rigor for developing some of the indicators.

In practice there are generally five methods to estimate a reference condition. We place our indicators in this context, following Stoddard et al. (2006). These are ordered, roughly, from most to least rigorous, and are referred to throughout the remainder of this report:

I. Reference-site. This relies on quantifying the biological condition at a set of minimally, least-disturbed, or best-attainable sites.

II. Interpreting historical condition. For some indicators, it may be possible to examine datasets recorded at earlier (historic) times. One way we employed this method was to generate a series of scenarios that reflect the condition of the park at different time frames, especially with respect to significant natural events that were important for the park, or important management actions that have occurred.

III. Extrapolation from empirical models. This condition can be inferred by extrapolating from an empirical model that develops a functional relationship of condition (response) and predictive (explanatory) variables at known locations.

IV. Best professional judgment. This relies on the qualitative estimation of conditions from experienced biologists of the conditions in an area. It is desirable to the extent possible that the judgment considers the following: consistency with ecological theory and other experts, and documentation and clear description of the "rules" by which the expert came to his or her conclusions (after Stoddard et al. 2006).

V. Ambient distributions. This relies on using a distribution of indicator values that are currently observed over some region (e.g., 5% or 25% percentile value). One way to use this method is to place a park in its broader ecoregional context by developing the distribution of values from the full ecoregion and then examining what percentiles the park's values are with respect to the full distribution. Important limitations to note are that this method often involves an a priori decision about a threshold (e.g., 5 or 25%?) that is commonly arbitrary, it assumes that higher indicator values represent better conditions (or if lower values indicate better conditions, then ranking is reversed), and depends on the distribution of sites relative to the range of the indicator.

3.5 Estimate of Concern and Degree of Confidence

For each indicator, we provide an estimate of the *degree of concern*, using the reference condition where possible. This estimate is intended to provide guidance to park staff to distinguish those indicators that we believe should be of relatively low concern from those of relatively high concern. Although ideally our estimates would be based on quantitative data and a sound monitoring design, in practice we made rough estimates of park condition using general scientific knowledge and, for the most part, qualitative data. For each indicator we estimated the degree to which the available evidence and understanding of an indicator justified concern, placing it into one of three general categories: *low concern, high concern,* or *insufficient data and/or knowledge* (qualitative data and/or understanding were not sufficient to make even a general determination; more research and data collection are warranted.)

We also provide our estimates with the *level of confidence* we have in an indicator in terms of its ability to provide reliable insights to a particular aspect of ecological condition. We considered two separate but related elements of confidence based on a framework developed by the U.S. Climate Change Science Program (USCCSP 2008). The first element is the amount of evidence that was available to assess whether an indicator provided strong guidance of ecological condition (e.g., if *high* then it would indicate that the topic is well-studied and understood). The second element is the level of agreement or consensus across the different lines of evidence regarding an indicator, including literature, expert opinion, and datasets. We rated the level confidence according to the following criteria:

> *High/moderate/low amount of evidence* - Is this indicator well-studied and understood, or instead is it mostly experimental or theoretical and not well-studied? Does your experience in the field, your analyses of data, and your understanding of the literature indicate that there is a high/low amount of information on the degree to which this indicator provides guidance about ecological condition?
>
> *High/moderate/low amount of agreement* - Do the studies, reports, and your experience in the field, analyzing data, or use of this indicator reflect a high degree of agreement on the effectiveness of this approach, or does it lead to competing interpretations?

Chapter 4. Natural Resource Conditions

The goal in developing the indicators of condition was to provide a suite of indicators that would help managers and scientists interpret the condition of important park resources—incorporating as many resources and as much of the park as practical. Because this is an initial, comprehensive assessment, it was important throughout the project to document our assumptions and logic for findings, describe the level of confidence, identify critical data gaps, and to recommend approaches to further refine/quantify reference conditions over time.

4.1 Regional Context and Issue Characterization

The goal of this section is to provide a general discussion of park issues and stressors, particularly in reference to how well ecological systems are functioning or facing risks that currently impact resources, habitats, and/or watersheds. We also provide a brief analysis of two major issues for which we are able to readily generate a spatially-explicit map: visitor use (using accessibility) and beetle kill.

Conceptually, issues and stressors are typically aligned along a continuum from low to high, where areas with low stress generally have a relatively natural condition (Figure 13; Davies and Jackson 2006). This conceptual model is helpful to understand the relationship of biological condition to stressor gradient. However, we believe that it is not the place for the natural resource condition assessment to provide a synthetic summary score for the park. The scope of the assessment, the variety of ecological systems, and the complex interactions do not warrant a combined, synthetic score. Rather, the best use of this assessment is to provide a baseline of indicators with spatially-explicit data that can be further analyzed and synthesized by park scientists and managers to develop a deeper understanding of condition.

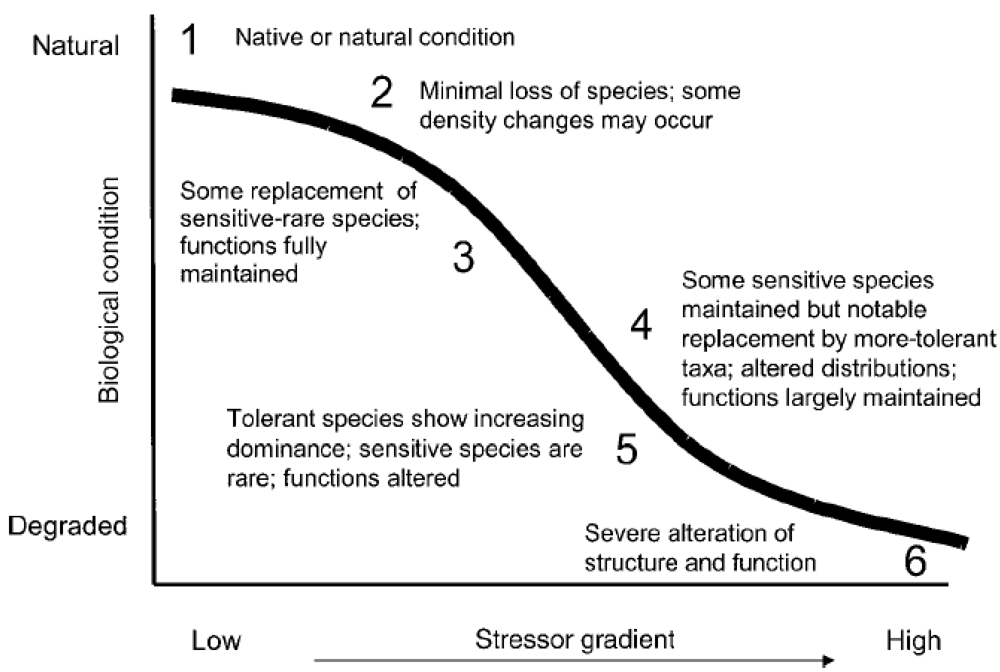


Figure 13. Conceptual model depicting stages of change in biological conditions in response to an increasing stressor gradient (Davies and Jackson 2006).

Similar to the ecological indicators, we have found it important to make reference to a comprehensive, logical structure or framework to examine issues and stressors. To characterize the issues to the park, we chose to use the *Unified Classification of Direct Threats* framework, because it is a comprehensive, hierarchical classification of threats. In this framework, a direct threat is the "…proximate (human) activities or processes that have caused, are causing or may cause the destruction, degradation and/or impairment of biodiversity and natural processes. This is synonymous with *sources of stress* and *proximate pressures*." This is a hierarchical framework containing three levels of classes with full definitions (the first two class levels are provided in Table 9). It is important to note that we considered a number of other approaches, such as the EPA's Ecological Risk Assessment framework (USEPA 1998), the Ecological Risk Index (Mattson and Angermeier 2007), and the Human Threat Index (Sowa et al. 2008), but we did not pursue these because these indices are based on arbitrary assignment of qualitative risk, which is fraught with difficulty.

Table 9. Unified Classification of Direct Threats, first two class levels.

Level 1	Level 2
1. Residential & commercial development	1.1 Housing & urban areas 1.2 Commercial & industrial 1.3 Tourism & recreation
2. Agriculture & aquaculture	2.1 Annual & perennial non-timber crops 2.2 Wood & pulp plantations 2.3 Livestock farming & ranching 2.4 Marine & freshwater aquaculture
3. Energy production & mining	3.1 Oil & gas drilling 3.2 Mining & quarrying 3.3 Renewable energy
4. Transportation & service corridors	4.1 Roads & railroads 4.2 Utility & service lines 4.3 Shipping lanes 4.4 Flight paths
5. Biological resource use	5.1 Hunting & collecting terrestrial animals 5.2 Gathering terrestrial plants 5.3 Logging & wood harvesting 5.4 Fishing & harvesting aquatic resources
6. Human Intrusions & disturbance	6.1 Recreational Activities 6.2 War, Civil Unrest & Military Exercises 6.3 Work & Other Activities
7. Natural system modifications	7.1 Fire & fire suppression 7.2 Dams & water management/use 7.3 Other ecosystem modification
8. Invasive & other problematic species & genes	8.1 Invasive non-native/alien species 8.2 Problematic native species 8.3 Introduced genetic material
9. Pollution	9.1 Household sewage & urban waste water 9.2 Industrial & military effluents 9.3 Agricultural & forestry effluents 9.4 Garbage & solid waste 9.5 Air-borne pollutants 9.6 Excess energy
10. Geological events	10.1 Volcanoes 10.2 Earthquakes/tsunamis 10.3 Avalanches/landslides
11. Climate change & severe weather	11.1 Habitat shifting & alteration 11.2 Droughts 11.3 Temperature extremes 11.4 Storms & flooding

At the scoping workshop, we elicited a list of major park issues for ROMO managers and scientists (recall Table 7). Using the unified classification of threats, we cross-walked the issues raised by park managers with the ROMO indicators. This resulting table (Table 10) is intended to provide a way to: a) organize the issues identified by park scientists and managers; b) examine which indicators we anticipate will be sensitive to an issue – that is, that will change in response to a change in issue; c) identify potential additional or future sources of issues to the park; and d) identify data and knowledge gaps. Note that the intent of this assessment was not to provide an indicator for every park issue.

Table 10. Synthesis of park issues of concern, placed within the classification of issues, with the indicator that addresses a particular issue.

Threat (Level I)	Park Issues of Concern	Indicator
1. Residential & commercial development	Wildland Urban Interface and adjacent high fire risk areas	Landscapes → Natural landscapes metric
	Prescribed fires and wildland fires in wilderness	
2. Agriculture & aquaculture	Nitrogen emissions from Front Range row crops and feedlots are sources of atmospheric N deposition	Condition of alpine lakes and atmospheric deposition
3. Energy production & mining	Nitrogen and mercury emissions are sources of atmospheric deposition	Condition of alpine lakes and atmospheric deposition
4. Transportation & service corridors	Nitrogen emissions are sources of atmospheric N deposition	Condition of alpine lakes and atmospheric deposition
	Increased visitation related to park shuttle system Shuttle impacts and related increased impact to resources	*
5. Biological resource use	None listed.	
6. Human Intrusions & Disturbance	Visitor impacts to wildlife (e.g., bighorn stress at Sheep Lakes, introduction of pathogens, habituation of wildlife – bears and coyotes with food rewards)	
	Visitor impacts in backcountry areas (noise, increase use in remote areas of the park, social trails, human waste and water quality)	Water → Extent & connectivity of wetland/riparian areas
	VERP/carrying capacity/crowding	**
	Shifts in visitor use due to aging baby boomers, and increasing thrill seekers with no or little environmental ethics?	
7. Natural system modifications	Lack of beaver	Biotic integrity → Extent of suitable beaver habitat
	Lack of native predators (wolf and grizzly bear)	Landscapes → Natural landscapes metric
	Diminishing populations of certain species (e.g., boreal toad, bighorn sheep, river otter, mink, peregrine falcon)	
	Water diversions (e.g., Grand Ditch)	Water → Extent & connectivity of wetland/riparian areas
	Fire in the montane and sub-alpine zones: inside or outside the natural range of variability?***	
	Changes in landscape dynamics due to bark beetles and forest diseases	Landscapes → Extent & proportion of major ecosystem types
	Jurisdiction over park species ranges and the challenge of coordination with CDOW in cross boundary wildlife issues.	
8. Invasive & other problematic species & genes	Overabundant ungulate species (elk, moose and possibly mule deer) and impacts on herbivory, habitat, and hydrologic processes	
	Disease pathogens that may lead to population declines (chytrid, CWD, whirling disease)	
	Nonnative wildlife threatening native populations (mountain goats, rainbow trout, brook trout, brown trout, rock dove, European starling, and a gray line species – moose)	Biotic integrity → Extent of native and non-native fish distributions
	Species not yet in the park but nearby – Quagga mussel (in Shadow	

Threat (Level I)	Park Issues of Concern	Indicator
	Mountain Lake), New Zealand mudsnail	
	Invasive exotic plants and their impacts - are new species becoming established and existing species moving into higher elevation areas due to climate change and drought?	Biotic integrity → Extent of exotic terrestrial plants
	Black bear conflicts with campers	
	Landscape impacts from bark beetle, blister rust, mistletoe, especially in high-value tree areas such as campgrounds, visitor centers, picnic areas, national register site districts and structures	
9. Pollution	Poor visibility	
	Atmospheric deposition and changes in micro-organisms in water and soil due to atmospheric deposition	Air and climate → Condition of alpine lakes and atmospheric deposition
	Rigidity of state air quality regulations and how those regulations greatly limit any future prescribed fire operations.	
10. Geological events		
11. Climate change & severe weather	Diminishing water and water quality due to climate change, drought and reduction in snowpack	
	Uncertainty of long-term sustainability and sensitivity to climate change for native species such as the pika, rosy finches, white-tailed jackrabbit, white-tailed ptarmigan, black swift and others	

*See related work by P. Newman on soundscapes and visitor use.
**This is not an indicator per se, but see maps of accessibility that approximate visitor use below.
***See Sibold et al. 2007.

4.1.1 Estimating Visitor Use through Accessibility Modeling[2]

One of the main issues identified by park managers is visitor use within the park. Consequently, we estimated visitor use through accessibility modeling to assist in identifying watersheds and ecological systems that are particularly vulnerable to visitor use.

Understanding the degree to which visitor use affects park resources is a critical need, and is considered by the park managers to be an important issue. Estimating visitor use is critical to the management of natural areas in order to inform how visitor use might affect natural resources and social conditions. However, many land management agencies have insufficient visitor monitoring programs and little baseline data about visitor use patterns and trends (Watson et al. 2000). A survey of wilderness managers reported that 63% of managers relied on best guesses to estimate visitor use. Some reasons why wilderness use has not been examined adequately include lack of funding and logistical problems resulting from size of area, number of access points, lack of personnel time, and lack of knowledge and training about available methods to collect and analyze data (Watson et al. 2000).

A few methods have been developed to estimate the spatial distribution of visitor use, though many of these are applicable to urban land cover types (e.g., Brown and Vivas 2005) or rely on incremental buffers from roads (e.g., Lesslie et al. 1988; Aplet et al. 2000; Sanderson et al. 2002; Theobald 2003) or distance (as a continuous variable) from roads (e.g., Riitters and Wickham 2003; Watts et al. 2007). One notable example of estimating visitor use specifically for protected areas is Shumacher et al. (2002) who developed a “human use intensity” model. This is computed as an equal-weighting of population density and road/trail density rasters (weighted using 3 for improved roads, 2 for unimproved roads, and 1 for trails) using a 1 km radius moving window. Rather than using road and trail density, which does not differentiate back-country from front-country locations, we developed an estimate of visitor use based on accessibility (Geertman and van Eck 1995; Nelson 2008) or remoteness (Carver et al. 2002) –defined as the one way travel time for an average visitor to any location within the park. Accessibility is a strong surrogate of visitor use, which has been found to be related to travel time and distance from a trailhead (van Wagtendonk et al. 1980; Pettebone et al. 2006). Note that this does not estimate the distribution of visitors (e.g., a density map of visitors); however, a useful next step would be to estimate of the number of park visitors moving across the landscape.

To understand how the issue has changed from previous “natural” conditions to the current state, we developed accessibility surfaces to reflect three scenarios:

- Scenario A. Current roads and trails: This scenario is based on the current transportation infrastructure (i.e., roads and trails), and travel time is the weighted average from the four main park entrances.
- Scenario B. Current roads without trails: This scenario reflects the road transportation infrastructure, but does not include the trail system. This allows us to examine how the current trail infrastructure modifies the “natural” accessibility to ecological systems in the park.

[2] Note that parts of this section are published in Theobald et al. (2010).

- Scenario C. "Natural" conditions without roads or trails: This scenario reflects no transportation infrastructure (i.e., roads or trails) in the interior of the park. This allows us to examine how the "natural" accessibility to ecological systems varies within in the park.

Methods

We used cost-distance techniques in ArcGIS to create "accessibility" models to estimate travel time to all locations within ROMO (Theobald 2005; Frakes et al. 2008). We conducted this analysis using 10 m resolution raster datasets that included data on roads, trails, slope, streams, and land cover (vegetation) types (Table 11).

Table 11. Listing of the datasets, attributes, and scale of data used to generate the accessibility maps.

Factor	Source	Attribute variables	Scale (grain)
Roads	ESRI StreetMap (1:100K)*	Posted speed limit	1:100,000
Trails	Colorado Trails dataset (Linn et al. 2008)*	Surface type, mode of travel, trail gradient, trail heads, parking lots	1:1,000-24,000
Topography	USGS National Elevation Dataset	Elevation (m), off-trail slope	10 m
Hydrography	USGS National Hydrography dataset, ROMO hydrography	Streams, lakes, stream order	1:24,000
Land cover	ROMO vegetation (Salas et al. 2004)	Reclassified to major land cover types	10 m

*We used these datasets because some trails in the Bear Lake corridor and outside of the park were not mapped correctly, and these provide infrastructure outside of the park (e.g., north access from Pingree Park area).

Generally, there are four steps to develop an accessibility surface to compute the time it would take a person to travel (one-way) to a given location: 1) from a starting location; 2) along road infrastructure to a trailhead; 3) from a trailhead along the trail infrastructure; and 4) off-trail across the landscape to all locations in the park.

First, we defined the starting (initial) locations to be the main entrances to the park (Table 12). There are three formal entrances: two on the east side (Beaver Meadows and Fall River) and one on the west (Kawauneechee). We added an additional "informal" trail entrance on the north side of the park near Long Draw Reservoir. Also note that there are four additional informal "entrances" accessible via trailheads on the east side of the park: Lily Lake, Twin Sisters, Lumpy Ridge-McGraw Ranch, and Dunraven. On the west side there are also four informal trailhead entrances: Tonahutu, Summerland Park, East Inlet, and Shadow Mountain Dam.

We developed a separate accessibility surface (in minutes of travel time) from each of the four starting locations. We combined these by finding the weighted average travel time—weighted to reflect the approximate distribution of visitors entering each gate, based on the 1996 park visitation survey. We also adjusted the weights for each layer spatially so that locations close to each entrance were more important in determining the overall travel time (using inverse distance as a relative weight). This is necessary so that extremely long (and unrealistic) travel times do not outweigh nearby estimates.

Table 12. Weights used to reflect the proportion of park visitors entering ROMO from each of the four main park “entrance” locations. (Unpublished data 1996). *Estimated by authors.

Entrance	No. of respondents	Weight
Beaver Meadows	1,388	0.43
Kawaneeche	721	0.22
Fall River	1,134	0.34
Northern*	40	0.01

The second step was to incorporate travel time along the road infrastructure. We assumed that visitors would travel via automobile along the roads at the assigned speed limit, and stop only at parking lots and designated trailheads. This is an important distinction from most accessibility models (e.g., Theobald 2005; Frakes et al. 2008) that model travel time off-trail directly adjacent to roads—which assumes that a visitor can stop at any location along a road, leave the car, and begin hiking away from the road. This was accomplished by weighting off-road and off-trail cells that were directly adjacent to road cells a modifier weight of 0.01. For gravel/4-wheel drive roads, we assumed a speed limit of 15 mph. Note that we assume automobile travels are unaffected by the steepness of roads.

The third step was to model travel time from trailheads and parking lots, along trails assuming visitors would be hiking (walking). Typical walking velocity for a hiker is 5 km/hr on flat terrain but diminishes on steeper terrain. We used the hiking velocity equation of (Imhof 1951) to reflect changes in travel speed as a function of trail gradient (or slope):

$$w=6*\exp(-3.5* |S + 0.05|)$$

where w = walking velocity and S = slope = tan (theta). Note that we do not distinguish travel direction (i.e., walking up a steep trail might take longer than down a steep trail).

The fourth step was to incorporate travel time due to off-trail hiking. Travel was assumed to be the same speed as the on-trail, but with an additional cost-weight applied to reflect the difficulty of moving through vegetation and crossing rivers and lakes. We assumed that hikers who plan to travel off-trail will use an existing (marked) trail to access the closest point to their off-trail destination. Areas where vegetation is denser—shrublands, for example—were weighted higher than areas where hiking velocity is less restricted, such as grasslands. Lakes and marshes were given an extremely high value to make travel through these areas virtually impossible. We generalized the 46 vegetation associations from the ROMO vegetation dataset (Salas et al. 2004) to 25 classes and estimated a modifier (1.0 no effect to 0.0001 nearly impassable) to reduce the travel speed (increase the cost weight or resistance). We also assigned a travel time modifier to large streams, rivers, and water bodies (Table 13).

Table 13. Travel time modifier for computing off-trail hiking speed. These values are multiplied by the on-trail travel time, so smaller modifier values mean slower travel speeds. These are estimates consistent with Frakes et al. (2008), which developed weights for coarser USGS National Land Cover Dataset cover types. Also, our weights for crossing larger streams (3^{rd} order and greater) is 3-10 smaller (and assumes it takes more time to cross).

Vegetation Class	**Modifier**
Barren	1.00
Blue Spruce	0.60
Cottonwood	0.90
Dead and Down woodland	0.30
Glacier	0.50
Herbaceous Upland Alpine	0.85
Herbaceous Upland Alpine Fell field	0.65
Herbaceous Upland Montane	0.85
Herbaceous Wetland Cross Zone - Marsh	0.45
Herbaceous Wetland Cross Zone - Wetland	0.45
Herbaceous Wetland Subalpine	0.45
Juniper	0.75
Krummholz	0.40
Lodgepole Pine	0.50
Mixed Conifer with Aspen	0.65
Montane Douglas Fir	0.65
Ponderosa Pine	0.75
Riparian Aspen	0.70
Riparian Montane Mixed Conifer	0.65
Shrub Riparian Cross Zone	0.35
Shrub Upland Alpine	0.45
Shrub Upland Lower Montane	0.45
Sub-alpine Conifer	0.50
Upper Montane Aspen	0.65
Water (lakes & reservoirs) Tributaries (1^{st} order) Small streams (2^{nd} order) Large streams (3^{rd} order) Rivers (>3^{rd} order)	0.0001 0.80 0.65 0.20 0.02

Results

Given the current road and trail infrastructure (Scenario A), the average one-way travel time for ROMO is 3.5 hours (Table 14). This means that the travel time from entrances to all locations in the park is, on average, 3.5 hours with a standard deviation of 2.3 hours. Roughly 7% of the park is within 1 hour; 50% is within 4 hours; and 80% of the park is within 8 hours. The west side of the park (west of the Continental Divide) is slightly less accessible, with an average one-way travel time of 3.8 hours, while it is 3.4 hours on the east side (Figure 14). The most accessible ecological system zones were savannah (2.0 hrs) and lower montane (2.3 hrs; Table 15). Note that these values are averages for the entire zones; there are some parts of each of these systems that are much more (and less) accessible than the mean value.

Table 14. Travel time in hours to locations within ROMO from four entrances for Scenario A (current road and trails infrastructure).

	Averaging Unit	Mean (hr)	STD (hr)
ROMO		3.5	2.3
Continental divide	East	3.4	2.2
	West	3.8	2.4
Ecological systems	Alpine	4.8	1.7
	Upper Montane	3.2	1.8
	Lower Montane	2.3	1.2
	Riparian	3.0	2.6
	Savanna	2.0	1.0

We also examined how travel time has changed as a function of the transportation infrastructure that has developed over time to its current extent. Figure 15 shows travel time without trails and shows travel time without roads or trails. Table 15. shows how average travel time increases from 3.5 hours (with roads and trails) to 3.9 (no trails but roads) to 7.4 (no roads or trails), and Table 16 shows travel times to RNAs.

Table 15. Summary of average travel time in hours for different accessibility scenarios in Rocky Mountain National Park.

Accessibility Scenario	Average (hr)	Standard Deviation (hr)
A. Roads and trails (current)	3.5	2.4
B. Roads only	3.9	2.6
C. No roads or trails ("natural")	7.4	3.4

Table 16. Average one-way travel time to Research Natural Areas in Rocky Mountain National Park reflecting different infrastructure scenarios.

Research Natural Area	A. Roads and Trails		B. Roads only		C. No roads or trails	
	Avg. (hr)	STD (hr)	Avg. (hr)	STD (hr)	Avg. (hr)	STD (hr)
Specimen Mountain	3.2	1.4	3.6	1.6	10.5	1.2
West Creek	4.8	1.0	5.2	1.1	5.8	1.5
Paradise Park	6.8	3.1	7.3	3.1	9.6	2.7

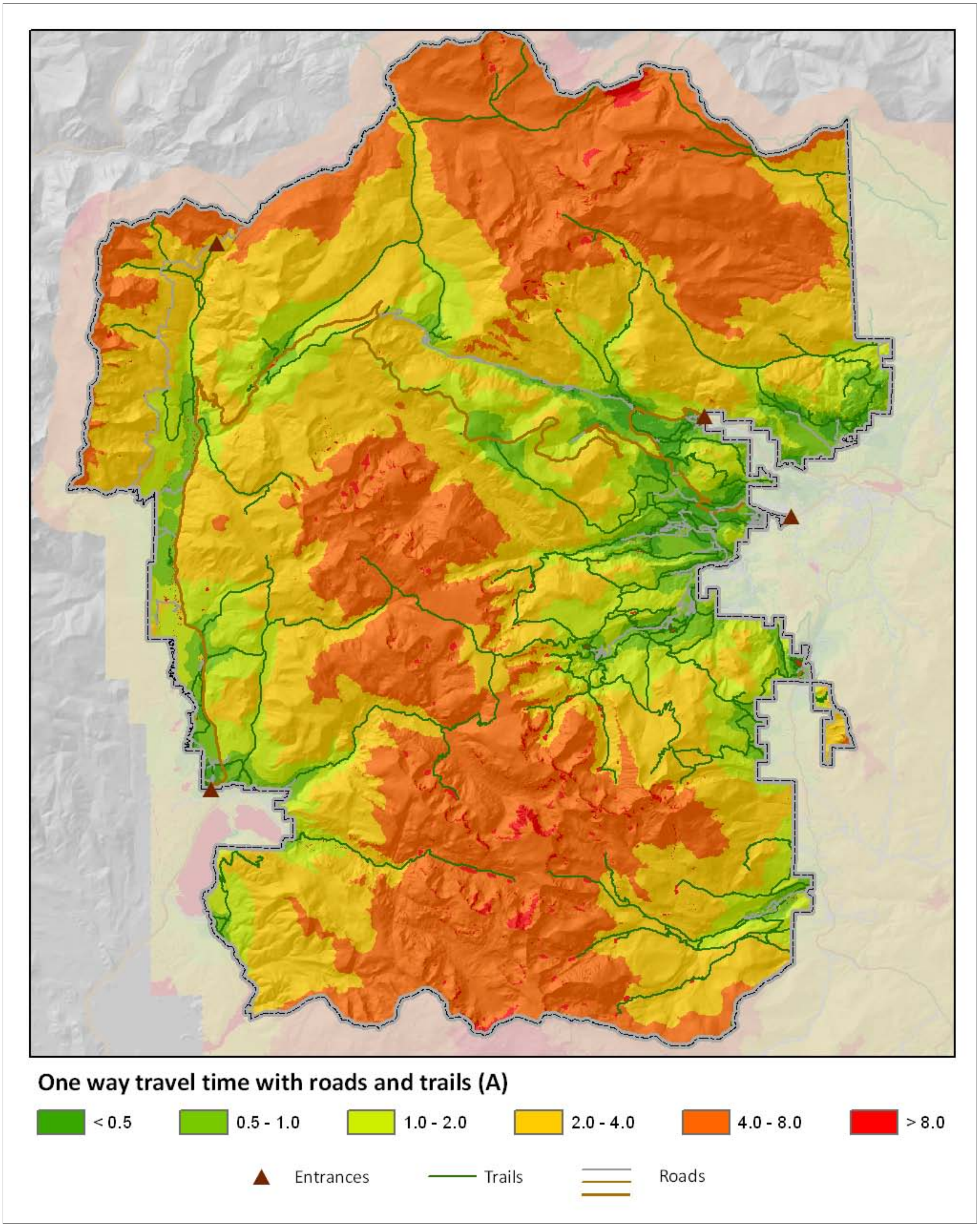


Figure 14. Accessibility within ROMO from main park entrances, assuming current transportation infrastructure (Scenario A)—shown as one-way travel time assuming shortest travel time along roads, trails, and off-trail.

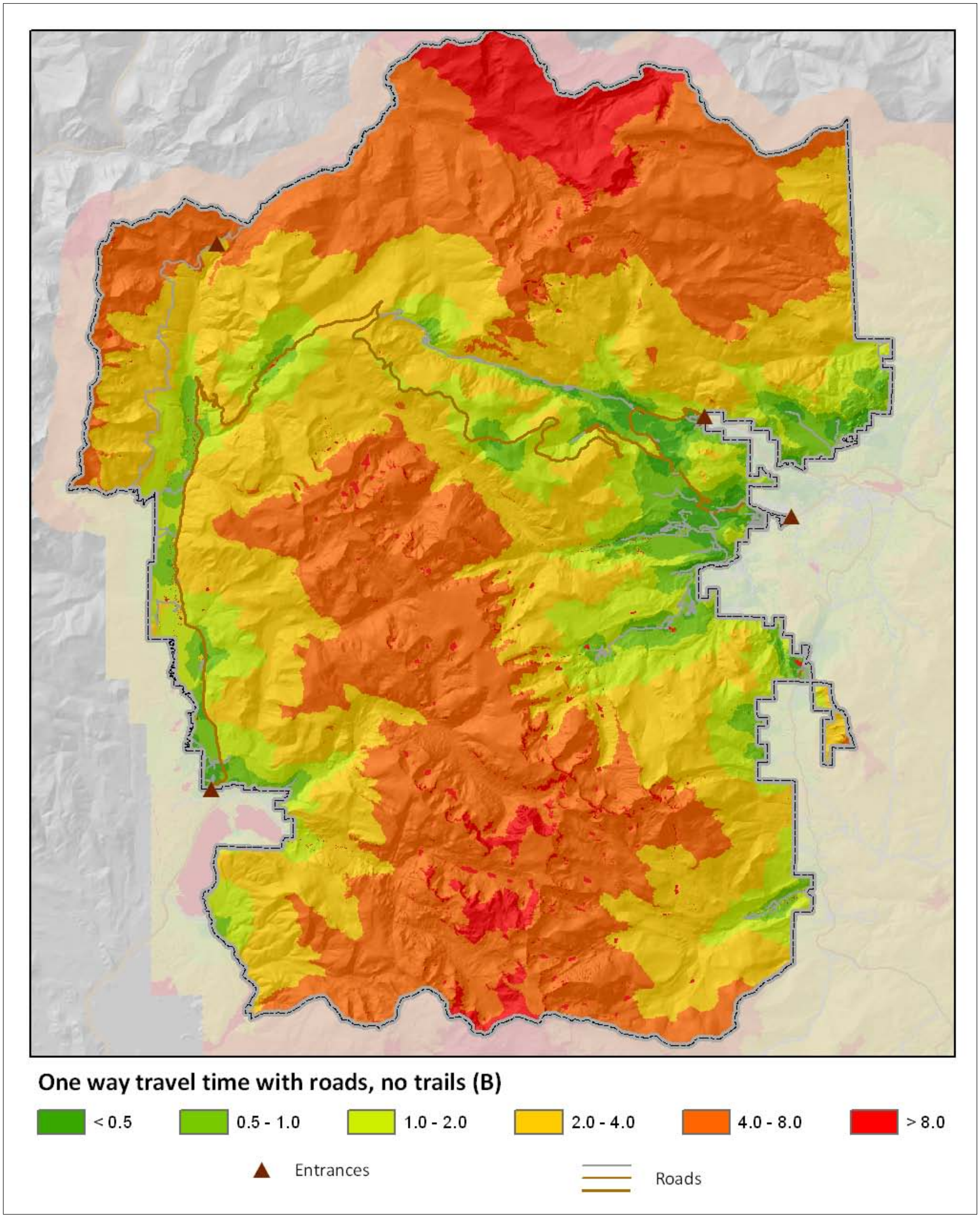


Figure 15. Accessibility within ROMO from park entrances, assuming no trails but roads as transportation infrastructure (Scenario B)—shown as one-way travel time assuming shortest travel time along roads.

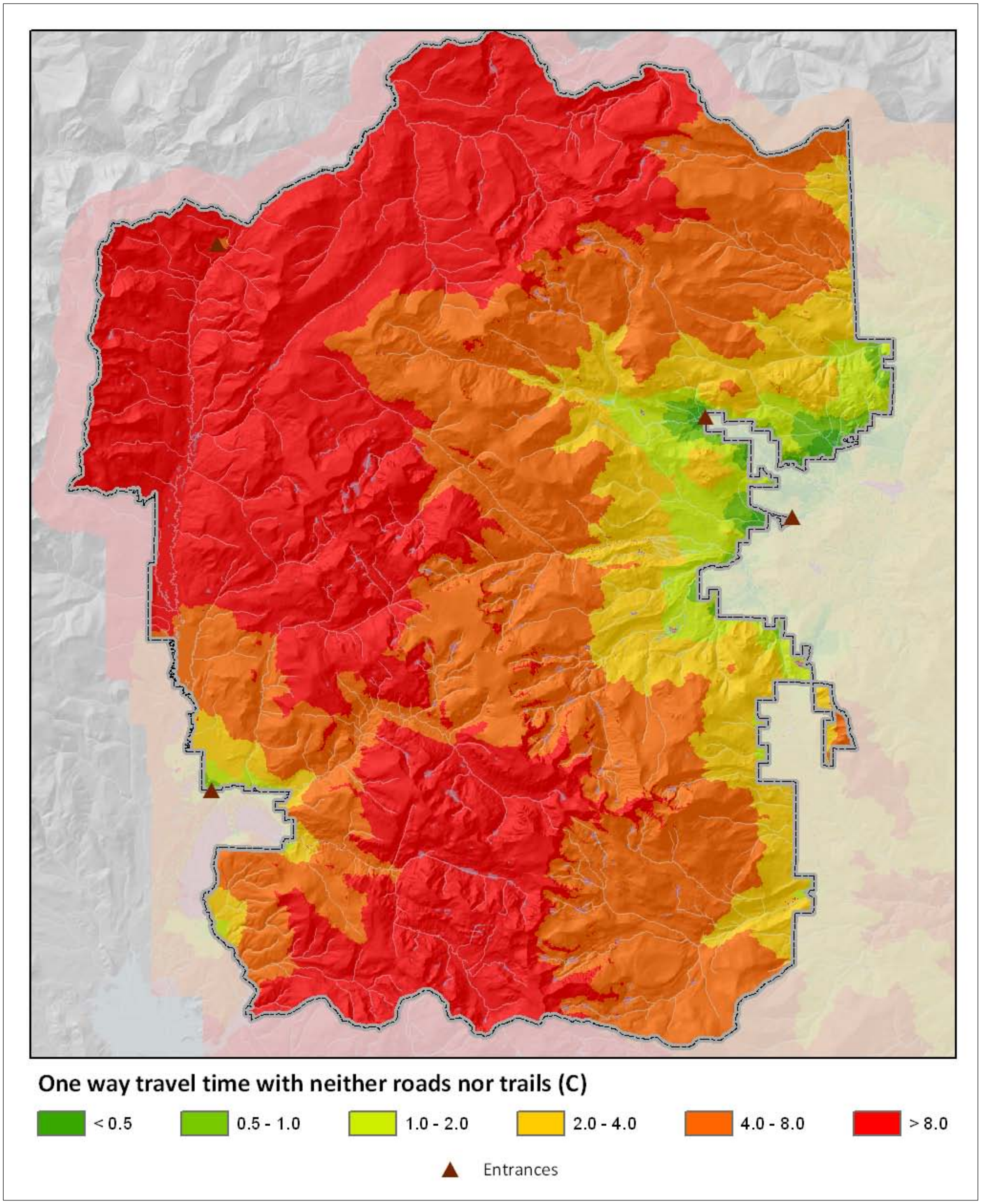


Figure 16. Accessibility within ROMO from park entrances, assuming no trails or roads as transportation infrastructure (Scenario C)—shown as one-way travel time.

Because the stated management goal for backcountry and Research Natural Areas is low impact, we compared the average accessibility of these areas to the rest of the park (Table 17).

Table 17. Average one-way travel time to different management zones in Rocky Mountain National Park.

Management zone	A. Roads and Trails	
	Avg. (hr)	STD (hr)
Research Natural Areas	6.5	27.2
Alpine tundra	4.8	18.2
Cross-country	4.2	11.1
Corridors	3.1	1.5
Front country	3.4	4.9
Not covered in BCMP	1.5	3.5

Another objective of this effort was to illustrate how accessibility could be used to inform the spread of exotic plant species. The average time to plots that contain cheatgrass was 0.86 hrs (SD=0.432), while the plots without cheatgrass were 3.24 hours away (SD=9.1; Figure 17). Cheatgrass occurs in more accessible areas—roughly 80% of plots with cheatgrass are within one hour's travel time.

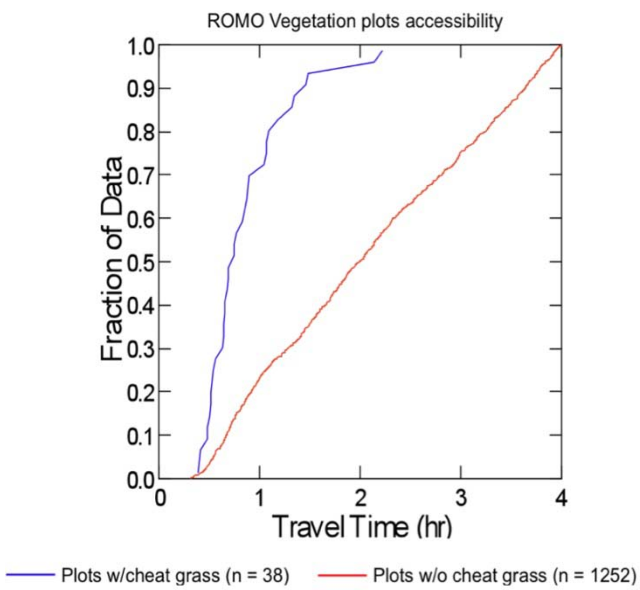


Figure 17. A cumulative distribution plot showing how the proportion of plots with cheatgrass relates to accessibility. The majority (80%) of the plots that have cheatgrass are within 1 hour travel time, whereas the majority (80%) of locations throughout the park are much less accessible (~3 hours travel time).

A few limitations to our approach should be noted. Most data we used were fine-scale (1:24K), but the spatial position of the roads in particular (from 1:100K scale) should be refined in future efforts. The goal of accessibility modeling is not to estimate the distribution of visitors (e.g., a density map of visitors); rather it is to estimate how accessible any location in a park is to an average visitor, with the explicit assumption that more accessible areas tend to have more visitor use. A useful next step would be to estimate of the number of park visitors moving across the landscape by incorporating destinations/attractions (e.g., peaks, lakes, waterfalls, etc.), perhaps using recreation choice modeling (e.g., Termansen et al. 2004). This might also include more nuanced aspects of visitor use such as type of use (day/overnight), mode (hike, bike, horse, motorized, etc.), duration, and values orientation to use. Finally, although we have verified accessibility times in the field in an informal way, a rigorous study that develops empirical estimates of travel time for different users, mode of use, and permeability modifiers as a function of different land cover types would make estimates of travel time more precise.

4.1.2 Watersheds at Risk to Beetle Kill

We briefly examined the risk of watersheds to beetle kill. We used data from the U.S. Forest Service Region 2's Forest Insect and Disease Aerial Survey (www.fs.fed.us/r2/resources/fhm/aerialsurvey/download). This provides data on the location and type of vegetation disturbance associated with beetle kill. We overlaid the relatively coarse polygons drawn from the aerial survey with the ROMO vegetation data and removed cover types that would not likely be infested by beetles (e.g., herbaceous, rock/ice, water, etc.). We then summarized these refined infested polygons by computing their percentage of the full watershed (HUC-12) area. These summaries are provided Table 35, located in Chapter 5 (Natural Resource Condition Summaries).

4.2 Analyses of Indicators

4.2.1 Air and climate: Condition of Alpine Lakes and Atmospheric Deposition

Authors: Jill S. Baron, Katherine E. Williams, and Melannie D. Hartman

Description/Purpose

Freshwater aquatic ecosystems, due to their location at the bottom of catchments and watersheds, are literally the "sinks" into which terrestrial landscapes drain, making them both responsive to upstream disturbance, and good indicators of human-caused change (Baron et al. 2002). High elevation lakes serve as bellwethers of ecological change from climate change as well as the long-range transport and subsequent deposition of nutrients and pollutants that result from human activity. We compared the chemical solutes of alpine lakes across the Rocky Mountain chain that could serve as indicators of the influence of warming temperatures, land use change and production of dust, and industrial or agricultural emissions of nutrients such as nitrogen and pollutants such as organochlorines. We used the distribution of chemical parameters from 244 alpine lakes to establish a reference condition by which to evaluate the state of Rocky Mountain National Park lakes during the period 1997-2006. We used an ecosystem model to estimate changes in alpine acid neutralizing capacity since 1900. We also recount the history of atmospheric deposition of nutrients and pollutants to Rocky Mountain National Park derived from measured and EPA emissions reconstructions.

The effects of acid deposition on lake and stream aquatic ecosystems have been a concern in North America and Europe since the 1970s, due to well-documented effects of acidification on aquatic organisms (Charles 1991). Acid rain from sulfate (SO_4^{2-}) or sulfuric acid inputs can increase the acidity of lake waters to the point where concentrations of monomeric aluminum solution increases. Monomeric aluminum (Al) is toxic to fish and invertebrates (Charles 1991). Concentrations of SO_4^{2-}, acidity, and Al can reflect inputs of acid rain, along with measurable responses in fish health and viability, and invertebrate abundance and assemblages. Atmospheric nitrogen, mercury, and soluble organochlorines have more recently been shown to alter aquatic food webs and productivity, fish reproductive health and behavior, and even the health of organisms that consume fish, such as birds, small mammals, and humans (Vitousek et al. 1997, Fitzgerald et al. 1998, Blais et al. 1998). The deposition of dust can serve to import nutrients such as phosphorus to alpine systems (Sickman et al. 2003, Neff et al. 2008). Evidence of possible climate warming effects on high elevation lakes is beginning to emerge, as well. Several studies have noted unusually high concentrations of heavy metals, weathering products, and nitrate in alpine lakes below retreating glaciers and rock glaciers (Lafreniere and Sharp 2005, Williams et al. 2007, Thies et al. 2007, Baron et al. 2009).

The east side of Rocky Mountain National Park has received elevated atmospheric nitrogen deposition since about 1950, and there has been a strong connection between atmospheric nitrogen deposition and measurable east-side ecosystem effects at select lakes (Baron et al. 2000, Nanus et al. 2008, Elser et al. 2009a, 2009b). In these aquatic systems, those changes have been increased nitrate (NO_3^-) concentrations, possibly lowered acid-neutralizing capacity (ANC), altered algal assemblages, and increased primary productivity (Baron et al. 2000, Wolfe et al. 2003, Enders et al. 2008).

In this report we begin with a description of measured atmospheric deposition trends to ROMO and modeled deposition trends from 1900 to 2000. We follow with a spatial comparison of nutrients, physical parameters, and pollutant concentrations in alpine lakes in the Rocky Mountains. We also summarize the results from modeling studies to infer changes in chemical parameters in a few ROMO lakes over time. Our objective was to place select lakes of ROMO in a geographic and temporal perspective. This is especially helpful for exploring change brought about by atmospheric deposition, as regions with elevated N deposition have alpine lakes with high NO_3^- concentrations, while regions receiving acid rain often show a chemical response of low ANC and pH (Stoddard et al. 1999, Bergström and Jansson 2006, Nanus et al. 2008). We used the recent WACAP study(Landers et al. 2008) to address the condition of ROMO alpine lakes with respect to atmospherically deposited mercury and organic contaminants.

Changes in chemical and biological condition over time provide critical information about lake condition, particularly in response to changing inputs or conditions. Long-term monitoring programs, such as the Loch Vale watershed program, or the Niwot Ridge LTER provide long-term records for select lakes. There are few, if any, time series in national parks, however, that have directly measured a change in water quality of alpine lakes away from a pristine condition. Proxy information from lake sediment records and ecosystem models can be used to infer changes for some, but not all, chemical and biological conditions (Baron et al. 1986, Wolfe et al. 2003, Landers et al. 2008). The NPS Vital Signs program will also contribute information about the causes and consequences of change over time. In a rapidly changing world it becomes important to establish a scientifically defensible reference condition of environmental quality in order to be able to evaluate the current state of natural resources and chart excursions toward or away from the reference. This is particularly true for U.S. national parks, whose significance as representatives of naturally functioning ecosystems becomes more important as their surrounding landscapes become increasingly altered by human activities (Baron 2004).

We mention here, but do not discuss further, an additional force for ecological change in alpine lakes. Resource management to enhance recreational opportunities has influenced the biological integrity of some alpine lakes in ROMO. Stocking of non-native trout has been pervasive in the Rockies (Pister 2001; Freshwater connectivity indicator, this report). Fish introductions dramatically alter native communities and extirpate native fishes, zooplankton, and benthic invertebrates (Knapp et al. 2001a and b). Stocking practices were eliminated in the 1960s, and non-native trout now persist only where there are reproducing populations. In a national park whose mission is protection of naturally-functioning native ecosystems, non-native trout represent a departure from the minimally disturbed condition.

Approach/Methods

Measured Deposition Chemistry and Estimated Historical Trends

ROMO has two National Atmospheric Deposition Program/National Trends Network (NADP/NTN) sites, both located on the east side of the park. The lower elevation (2490 m) Beaver Meadows (CO19) site has been operating since 1980, and the higher elevation (3159 m) Loch Vale (CO98)site since 1983. Wet deposition trend data for major ions from both sites were taken from the NADP website.

Dry deposition of select gases and aerosols has been measured at the Clean Air Status and Trends (CASTNET) site ROM406 located on the eastern boundary of ROMO (2743 m) since 1995. Dry deposition trend data for nitrogen and sulfur were taken from the CASTNET website.

Estimated historical emissions of NO_3^-, NH_4^+ and SO_4^{2-} deposition to Loch Vale Watershed were based on emissions (EPA NEI 2004, http://www.epa.gov/air/data/) of NO_x and SO_2. Using an estimated background nitrogen deposition value of 0.5 kg N ha^{-1} yr^{-1} in 1900, and a 19 year record of measured values from Loch Vale (NADP site CO98), N deposition history was reconstructed using exponential equations that correlated well with EPA-reported NOx emissions from Colorado and from the sum of emissions of 11 western states. Full methods are described in Baron (2006). The 1984-2001 measured SO_4^{2-}concentrations at Loch Vale Watershed (NADP/NTN site CO98) were correlated with Western U.S. SO_2 EPA-reported emissions (R^2=0.55). The relation between emissions and measured concentrations was used to hindcast annual SO_4^{2-}concentrations back to 1900. As with N deposition, precipitation values from a climate reconstruction model (VEMAP 1996) were multiplied by concentrations to derive annual SO_4^{2-}deposition values for Loch Vale Watershed.

Sources of Lake Data
We gathered lake data from federally-protected lands of the Rocky Mountains of Alberta, Montana, Idaho, Wyoming, Utah, and Colorado (Table 18). Eighty of the lakes were in Colorado. There are thousands of alpine lakes in the Rocky Mountains. A subset of these lakes has been sampled for water quality parameters, so the following analysis is not unbiased as much as opportunistic. Our selection criteria for inclusion of a lake in the analysis were:

- lake or lake outlet sample collection and analysis using established protocols for low-ionic strength waters and adequate quality assurance protocols similar to the Loch Vale Watershed Long-term ecological research and monitoring program and the Western Lake Survey;
- location above treeline;
- sampled one or more times during late summer season (July 15-October 31) during the years 1997-2007.

Lakes were not screened based on parent material. Although bedrock composition is a common criterion for identifying lakes susceptible to acidification, it does not pertain to other types of disturbance that could degrade lake condition, such as deposition of nutrients (N, P), contaminants (organochlorines, metals), or climate change. The data sources, described in Table 18, represent most of the alpine lake samples collected in the Rocky Mountain region during the 1997-2007 period.

Statistical treatment of lakes
For lakes that had more than one sample event, means and medians of data values were calculated so that each lake had only one value within the set. There was no significant difference between mean versus median values (Student's T-Tests $p<0.05$), and means and medians are used interchangeably in this document. Physical and chemical information in common at all lakes included major ions, alkalinity, conductivity, and pH. Most lakes also reported late summer surface temperatures.

Once assembled, summary statistics were performed on the data set, followed by rank order graphing of each chemical attribute.

Table 18. Sources of lake chemistry data used for inorganic solute comparisons.

Data Source	Number of lakes from which lake data were assembled*	Lakes used for analysis**	Reference	Comments
USGS NWIS	21	21	http://waterdata.usgs.gov/nwis	Resample of lakes initially sampled in 1985 WLS
USFS	251	230	http://www.fs.fed.us/ARMdata/	Lakes selected for long-term monitoring from Wilderness level reconnaissance surveys in MT, ID, WY, UT, CO
CSU	22	22	Lafrancois et al. 2003, Nydick et al. 2004	CO and WY lakes collected for research

*includes lakes above and below treeline, multiple sample dates per lake
** some lakes were sampled by multiple groups, so the numbers do not add to 244

Models of pre-measurement stream chemistry
We used DayCent-Chem, a daily time-step ecosystem-hydrogeochemical model to investigate the changes in stream water chemistry that may have occurred in Andrews Creek, Loch Vale Watershed, over the past century. DayCent-Chem is a daily time-step ecosystem model that couples ecosystem nutrient cycling and plant dynamics with geochemical equilibrium equations (Hartman et al. 2007).We ran the model from the known ecosystem state in 1999 backwards to 1900 using daily historic VEMAP climate (VEMAP 1996) and hindcasts of N and S deposition described above.

Reference Condition
We define the reference condition assuming that alpine lakes of national parks and wilderness areas are minimally disturbed, after the *Minimally Disturbed Condition* (MDC) definition of Stoddard and colleagues (2006). The MDC describes the condition of waters in the absence of significant human disturbance, and Stoddard and colleagues state that once established, the distribution created by a group of sites in MDC should vary little over time and can serve as a nearly invariant anchor by which to judge current conditions (Stoddard et al. 2006). A lake could receive atmospheric contaminants but still fall in the minimally disturbed condition if the inputs fall below the threshold for observed biological effects. A second type of reference condition, the *Historical Condition* (HC), can be an accurate estimator of the true reference condition defining biotic integrity if the historical point chosen is before the start of any human disturbance (Stoddard et al. 2006). We use a combination of interpreting historical condition and ambient distributions to develop reference distributions.

There is abundant literature describing low concentrations for minimally polluted lakes and increasing concentrations with increasing atmospheric deposition inputs, but just how low is the true MDC (Bergström et al. 2005, Bergström and Janssen 2006, Elser et al. 2009a, 2009b)? We addressed this by comparing lake concentrations across the sample area, and matching low concentrations with low N deposition inputs.

Spatial comparisons are not useful for other analytes that have variable concentrations due to different parent materials. Conductivity, calcium, sulfate, and chloride concentrations can weather from certain bedrock materials, but their concentrations in a lake can also change over time due to inputs of dust or pollution. Our presentation of these values for ROMO therefore represents a HC against which future change can be identified. Acid neutralizing capacity and pH can be representative of parent material, but can also change with inputs of atmospheric deposition of acids or strong acid anions. Differences in concentrations of these chemicals between the east and west sides of ROMO, and the reconstructed water chemistry based on SO_x and NO_x emissions records are suggestive that deviation away from the MDC has occurred on the east side; this is discussed below. We infer the HC for some heavy metals, contaminants, and nutrients from lake sediment proxies of past conditions.

Results/Discussion

Measured wet and dry deposition trends
Long-term wet deposition monitoring shows changes and trends in the pattern of precipitation chemistry, with some solutes clearly increasing in deposition (and concentration; data not shown) and others clearly decreasing (
Figure **18**). Both the low elevation and the high elevation site, Beaver Meadows (CO19) and Loch Vale (CO98), displayed similar trends for wet deposition, although the total deposition was greater at Loch Vale, where precipitation amounts were higher. Calcium deposition has increased at Loch Vale at a rate of 0.03 kg $ha^{-}1$ yr^{-1}, while calcium at Beaver Meadows showed little change. Clear spikes in years such as 2005 suggest dust events. Total inorganic N increased at both sites, but the rate of change, 0.04 kg $ha^{-}1$ yr^{-1} at Beaver Meadows, was greater than at Loch Vale (0.01 kg $ha^{-}1$ yr^{-1}). Acidity and sulfate have both declined strongly at both sites, in keeping with regional trends of reduced SO_2 emissions. Chloride deposition has also declined. Concentration values for both sites had the same trend patterns as deposition (data not shown).

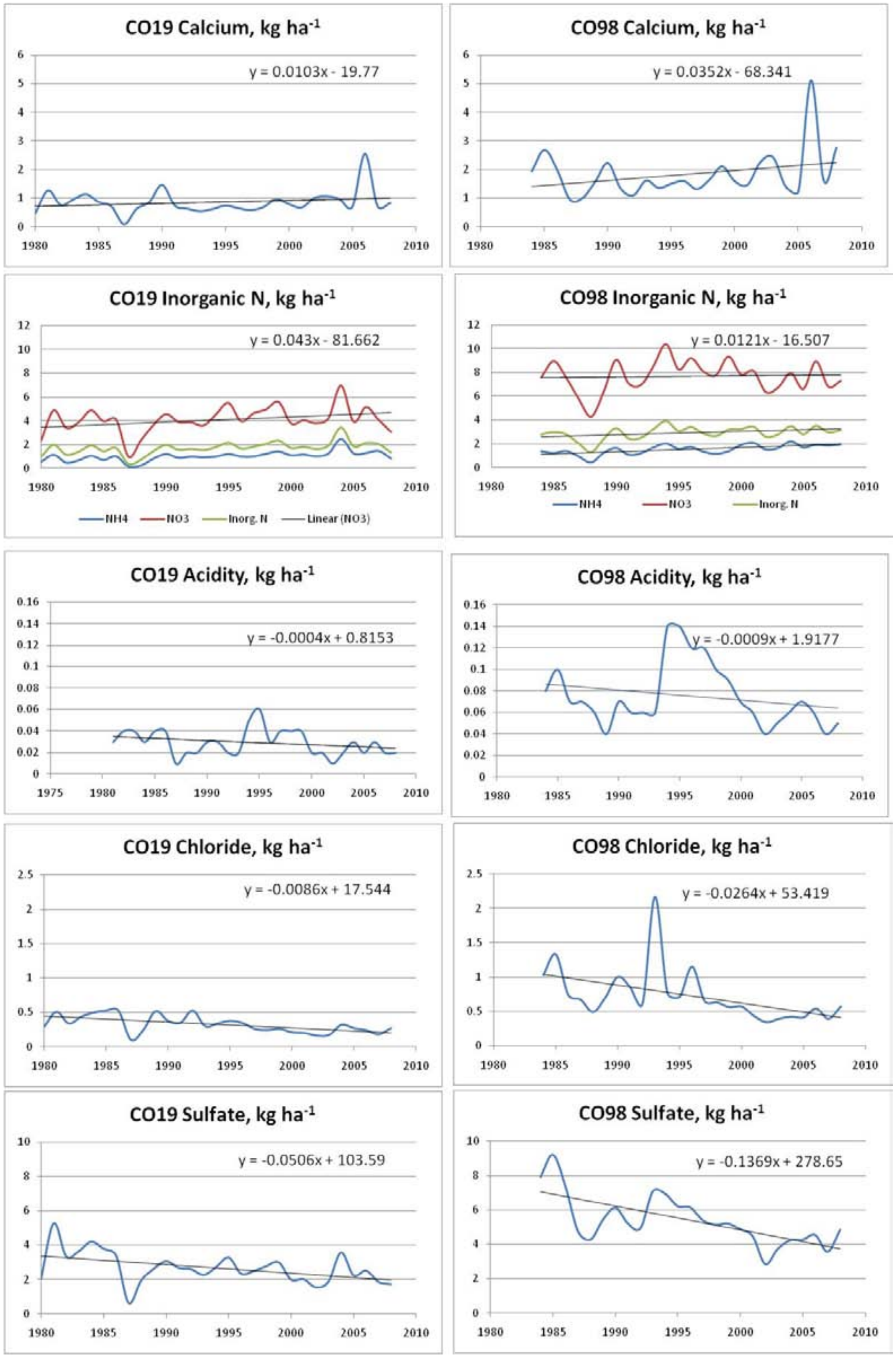


Figure 18. Wet deposition values over time for two NADP sites in ROMO, Beaver Meadows (CO19) and Loch Vale (CO98). Note that nitrate and ammonium concentrations are molecular, and not their nitrogen component, and thus are not directly comparable to the inorganic N values on the same figure. Inorganic N represents the sum of only the nitrogen portions of nitrate and ammonium. Linear trend lines are shown.

Dry deposition data (http://www.epa.gov/castnet/charts/rom406_wdn.gif), presented in Figure 19, suggest about a third of the total N and S deposition (wet plus dry) is deposited as dry species. Although statistical trend analysis is not possible since not all data are reported, there appears to have been a slight decline in dry deposited species since 1996. Gaseous ammonia is not reported, but contributes to the total N inputs.

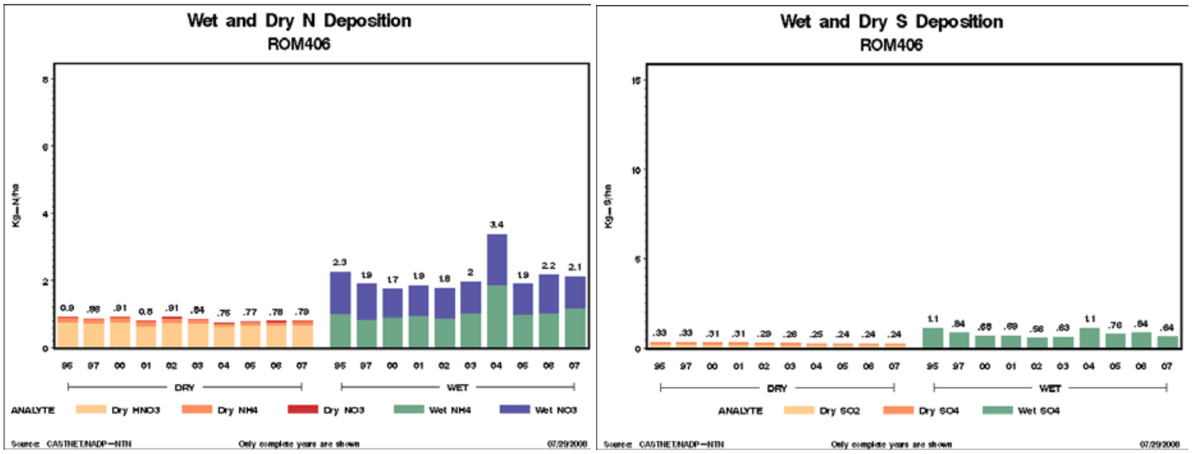


Figure 19. A comparison of dry deposition from the ROM406 CASTNET site and wet deposition from CO98, the Loch Vale site.

Estimated Historical Trends in Deposition

Hindcast deposition trends show an exponential increase in both nitrate and ammonium commensurate with increasing population growth in the West (Figure 20; Baron 2006). Sulfate concentrations were more variable with time, and seem to reflect major economic or social events, such as a depression in 1920-1921, the Great Depression from 1930-1940, an increase in industrial production during World War II, and the decline in regional copper smelting and implementation of the Clean Air Act beginning in the 1970s (Oppenheimer et al. 1985).

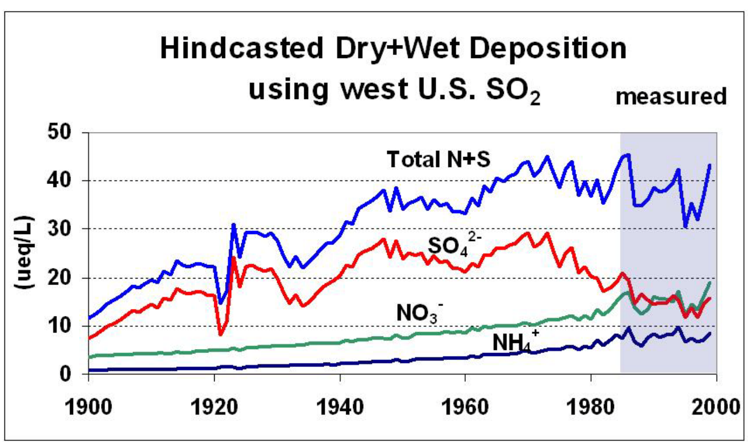


Figure 20. Reconstructed dry plus wet atmospheric deposition to Loch Vale Watershed from 1900 to 2000. SO_2 emissions from EPA were calibrated to measured SO_4^{2-} deposition to ROMO for 1984-2000. The relation was hindcast back to 1900. NO_3^- and NH_4^+ deposition was hindcast with an exponential regression from measured depositions values 1984-2000 back to estimated background values in 1900.

Rocky Mountain Regional Lake Comparison

Comparison with Western Lake Survey

Most of the lakes in our sample were selected for long-term monitoring by the U.S. Forest Service because of their suspected sensitivity to acid rain, thus they represent low ANC lakes on crystalline bedrock (http://www.fs.fed.us/ARMdata/). Thus it makes sense that the 224 alpine lakes in our survey were more dilute and with lower mean concentrations of most solutes than those from the 1985 Western Lake Survey (Landers et al. 1987; Table 19). Western Lake Survey lakes were selected through a stratified random sample to describe surface water chemistry on a regional scale. Concentrations of NH_4^+, NO_3^-, and SO_4^{2-}, were higher in our Rocky Mountain sample than Western Lake Survey means and median values. This type of comparison is important for context, and a comparison of minimum values for our sample with the values from the first quartile of WLS lakes (representing concentrations for the lowest 25% of lakes in their population) can help in the selection of values for the MDC.

Table 19. Summary Statistics for Select Alpine Lakes. Values presented are the mean and range of select physical and chemical characteristics of 244 alpine lakes included in the study. Lakes were included in the study if sampled between mid-July and late October, 1997-2007. <DL signifies the sample was below the analytical detection limits. Values to the right of the double line are the mean (median) and minimum values from the 1985 Western Lake Survey (Landers et al. 1987) for the entire 719 lakes in the WLS and for the 139 lakes in the Southern Rockies Region, for comparison.

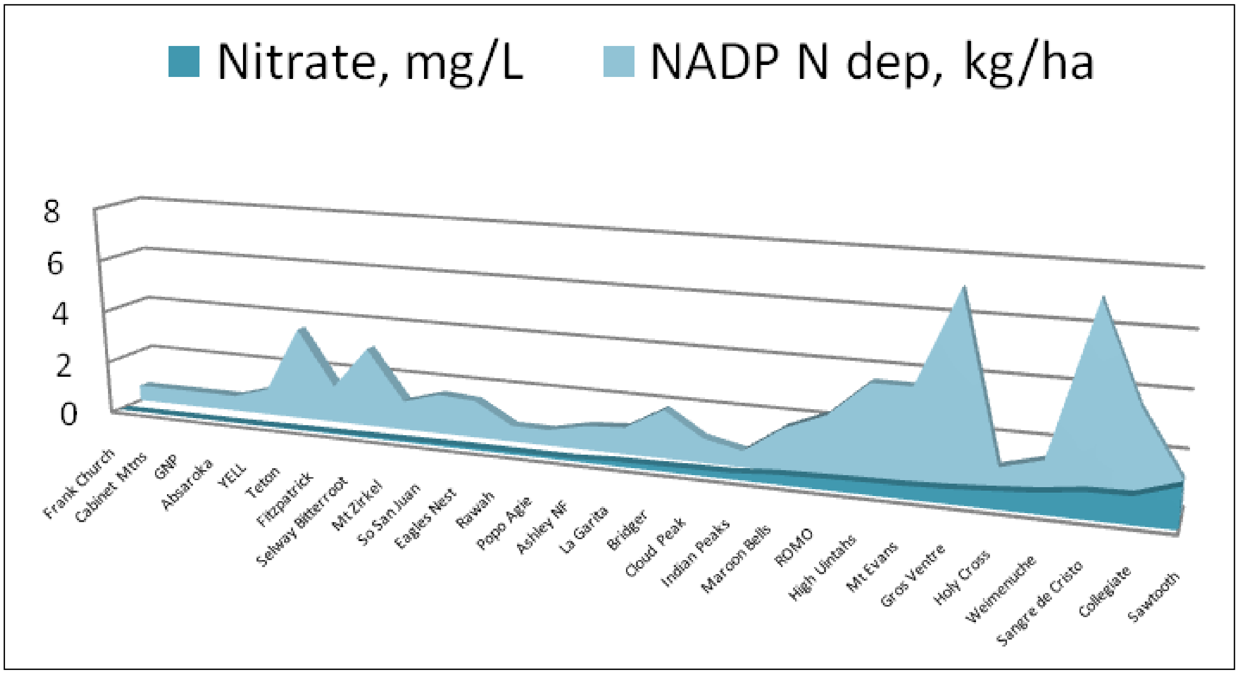
Attribute	Mean	Minimum	Maximum	**All WLS** Mean (median)	**All WLS** 1st Quartile	**WLS Southern Rockies** Mean (median)	**WLS Southern Rockies** 1st Quartile
Elevation (m)	3260	1921	4000	2466(2613)	1746	3164(3264)	2659
Temperature (˚C)	9.5	1.7	19	--	--	--	--
ANC (μeqL^{-1})	87.3	-3	1200	328(119)	54.5	598(317)	113.9
pH	6.7	5.7	8.3	7.3(7.2)	6.8	7.7(7.6)	7.1
Conductivity (μScm^{-1})	21.0	2.0	342.0	38.0(16.5)	8.4	70.4(37.1)	14.2
Ca^{2+} (mg L^{-1})	2.7	0.1	44.0	4.9(1.9)	0.9	10.2(4.7)	1.6
NH_4^+ (mg L^{-1})	0.03	<DL	0.6	0.01(0.0)	0.00	0.01(0.0)	0.00
NO_3^- (mg L^{-1})	0.5	<DL	7.4	0.1(0.02)	0.01	0.1(0.03)	0.01
SO_4^{2-} (mg L^{-1})	2.7	0.2	109.0	2.2(0.9)	0.3	5.8(1.7)	0.8
Cl^- (mg L^{-1})	0.1	0.03	1.2	0.4(0.2)	0.1	0.5(0.2)	0.1

As stated above, a spatial comparison of solutes is valuable for comparing chemicals deposited in atmospheric deposition, namely NO_3^- and NH_4^+. The mean concentration for all WLS lakes and Southern Rockies region of WLS lakes is 0.1 and 0.01 mg L^{-1} for NO_3^- and NH_4^+, respectively. The median and 1st quartile concentrations for NO_3^- were 0.03 and 0.01 mg L^{-1} for the Southern Rockies, while the median and 1st quartile concentrations for NH_4^+ were 0.01 and 0.00 mg L^{-1}. The MDC therefore is a value ≤0.1 mg L^{-1} for NO_3^- and ≤0.01 mg L^{-1} for NH_4^+.

In a comparison of median lake concentrations with wet atmospheric N deposition values from the year 2000 (NADP; http://nadp.sws.uiuc.edu/), one can see that high lake NO_3^- concentrations often, but not always, co-occur with the highest wet N deposition (Figure 21 top). The highest N deposition occurred in Colorado at Front Range NADP sites located near Indian Peaks, Mount Evans, ROMO, Rawah, as well as La Garita, South San Juan, and Mount Zirkel wildernesses. The highest median lake NO_3^- concentrations occurred in the Rawah, ROMO, Indian Peaks, Absaroka, Maroon Bells, Mount Evans, La Garita, and High Uintahs. Caution needs to be taken in interpreting wet deposition data from CO02, Niwot Saddle, since an overcatch problem from wind-blown snow produces abnormally high values (Williams et al. 1998).

Sampled wilderness lakes with the lowest median lake SO_4^{2-} concentrations are among the sites that also have the lowest wet SO_4^{2-} deposition values, but low wet SO_4 deposition values also occur where the median lake SO_4^{2-} concentrations are somewhat higher (Figure 21 bottom). The highest lake SO_4^{2-} concentrations occurred in the Holy Cross, Weimenuche, Sangre de Cristo, Collegiate Peaks, and Sawtooth Wildernesses samples, where the values may reflect sulfur-bearing minerals in the bedrock. With the exception of deposition values from CO02, Niwot Saddle, for the Indian Peaks and Mt. Evans Wildernesses, which may be abnormally high (Williams et al. 1998), wet SO_4^{2-} deposition seems to be uniformly low with values less than 2.0 $kgha^{-1}yr^{-1}$, or moderate, with values around 6.0 $kgha^{-1}yr^{-1}$.

We suggest caution in interpreting these figures. The density of NADP sites in the western U.S. is low, and most NADP locations are lower in elevation than alpine lakes. Weather patterns may differ between high and low elevations (Weathers et al. 2006) And even though lakes may be above treeline, if they are surrounded by tundra or wetland vegetation terrestrial N uptake may limit the movement of N from deposition to lakes (Sickman et al. 2002).



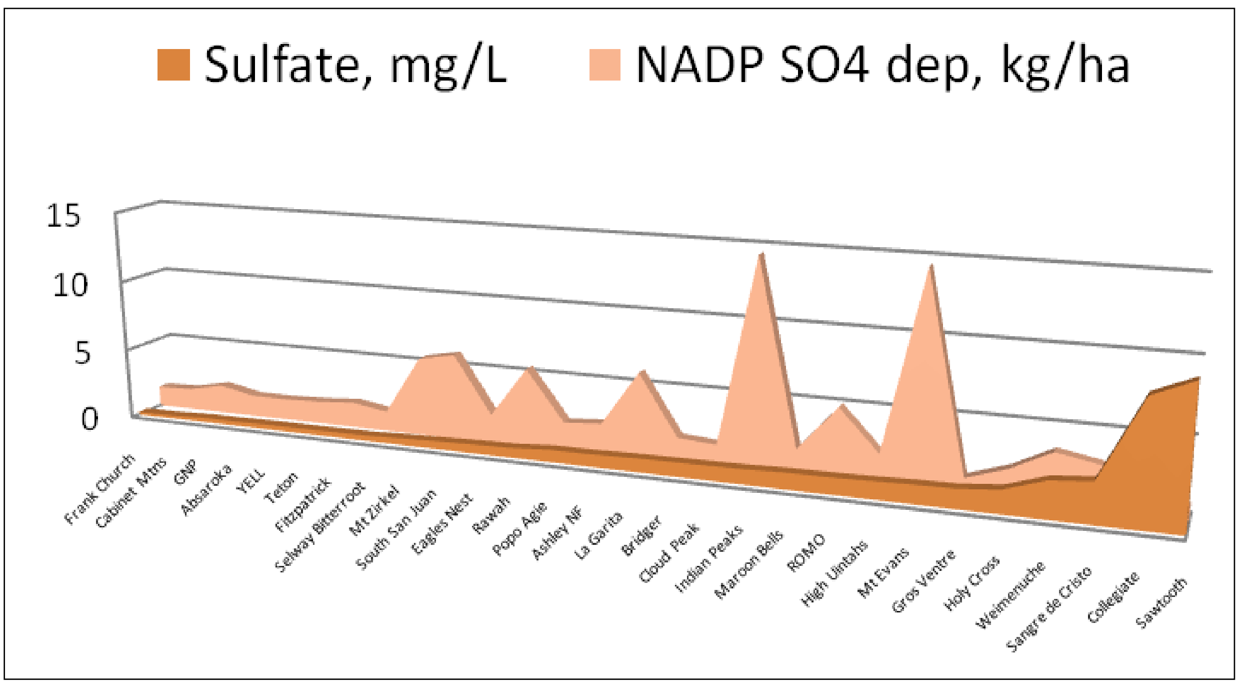
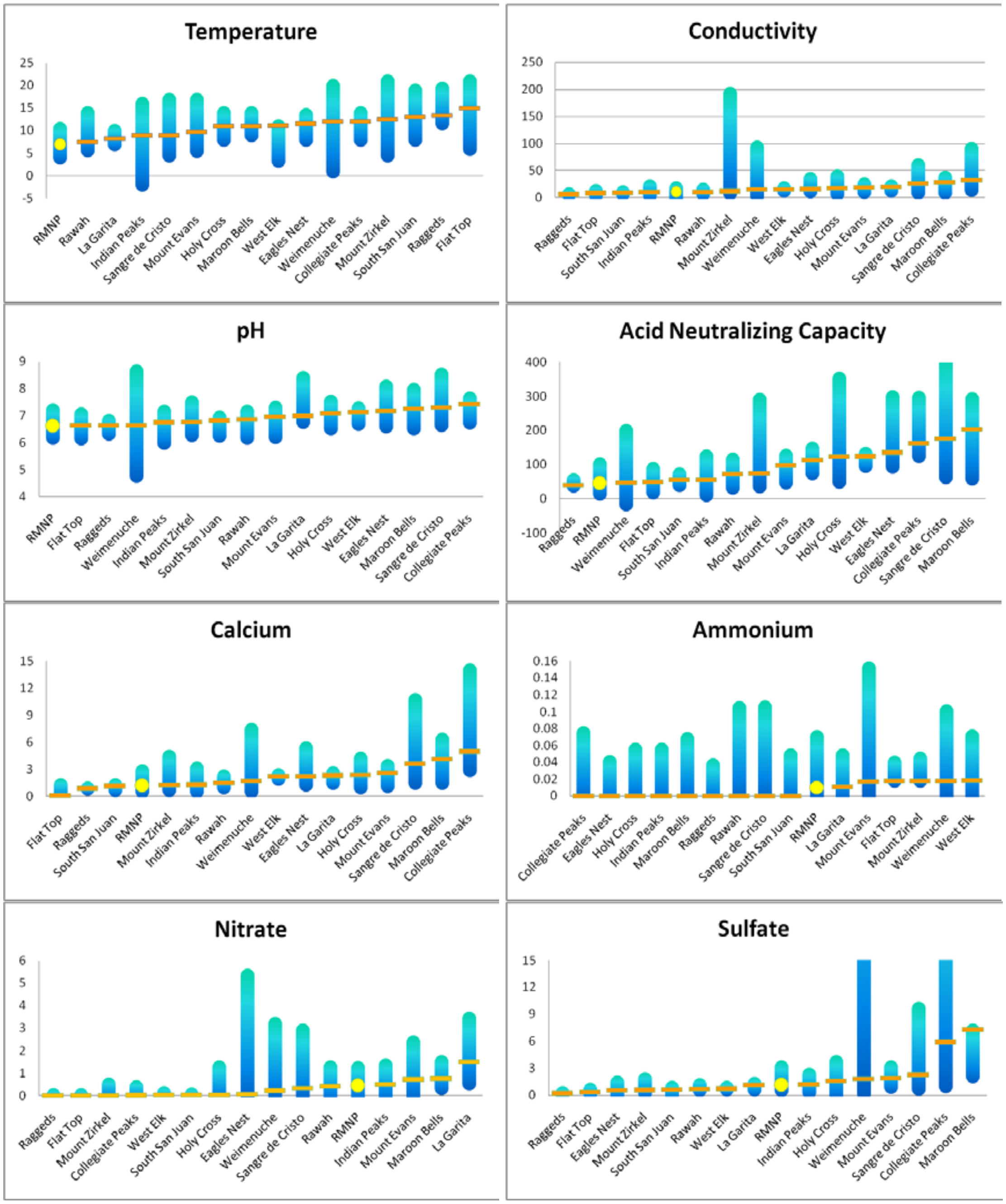


Figure 21. a) Wet N deposition (light blue) in $kgha^{-1}yr^{-1}$for 2000, and median lake NO_3^- concentrations in mg L^{-1} (darker blue); b) Wet SO_4^{2-} deposition (pink) in $kgha^{-1}yr^{-1}$ for 2000, and median lake SO_4^{2-} concentrations mg L^{-1} (orange), for sampled wilderness and park lakes of the U.S. Rocky Mountains. Deposition values were taken from the closest NADP site.

Comparison of ROMO lake sample with Colorado Wilderness Area sampled lakes

Even when compared with other Colorado lakes, ROMO lakes stand out as colder and more dilute (Figure 22). The lowest median pH (most acidic) and the second lowest ANC values were found in ROMO lakes. The concentrations of Ca^{2+} and Cl^- were low in ROMO lakes and the median sulfate concentrations were similar to most of the other lakes sampled. Median NO_3^- concentrations in the park were among the highest third of the ranked areas; wilderness areas with similar or higher nitrate concentrations included Rawah, Indian Peaks, Mount Evans, Maroon Bells, and La Garita. Median NH_4^+ concentrations were low, but measurable, in ROMO, unlike nine other wilderness areas that had values below detection limits.

The ranges of solute concentrations in ROMO lakes were narrower than those from many of the wilderness areas, suggesting that the ROMO lakes included in our sample were located on similar parent material and subject to similar atmospheric inputs. The wilderness areas vary greatly in size and the different mountain ranges of Colorado have many different types of bedrock materials; this is reflected in the range of concentrations especially in weathering products such as sulfate and calcium.



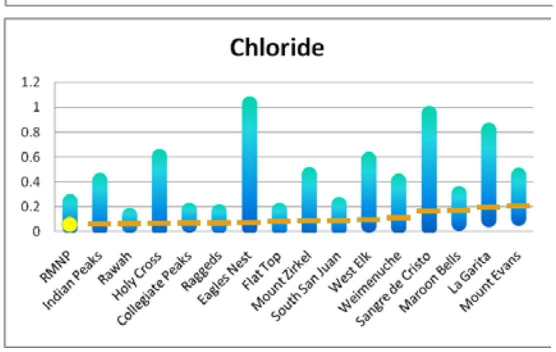


Figure 22. Ranked distributions from lowest to highest values of temperature and solutes from ROMO and Colorado Wilderness Areas. Blue bars delineate maximum and minimum values; horizontal lines are the median value of all samples. ROMO is distinguished by a yellow circle for the median. Temperature units are ºC, conductivity is in µS cm^{-1}, pH is in pH units, acid neutralizing capacity is in µeq L^{-1}, and all other values are in mg L^{-1}.

East vs. West ROMO Comparison

Within ROMO 25 lakes were sampled east of the continental divide and 7 on the west side (Table 20). ANC was about 30 μeq L^{-1} lower in the west side sites, while pH was about 0.4 units higher. Calcium, Cl^-, and NH_4^+ were similar in sampled lakes from east and west sides; conductivity was slightly higher in west-side lakes; and NO_3^- was 0.5 mg L^{-1} higher in east-side lakes. The values for NO_3^- and NH_4^+ defined above suggest that east side lakes have concentrations greater than the MDC, while the west side lakes can be classified as in their MDC. Knowing that there is a history of elevated atmospheric N deposition to the east side lakes (Baron et al. 2000), we infer that ANC and pH have been reduced by inputs on the east side, but since historical reconstructions of regional SO_4^{2-}deposition, described below, would have affected both east and west side ROMO lakes, it is not possible to simply use the east-west comparison for defining and ANC or pH MDC.

Table 20. Summary Statistics for ROMO Sampled Lakes East and West of Continental Divide. ANC is in μeq L^{-1}, Cond is conductivity, μS cm^{-1}, pH is in pH units and all other solutes are reported in mg L^{-1}.

	ANC	Ca^{2+}	Cl^-	Cond	NH_4^+	NO_3^-	pH	SO_4^{2-}
East mean (stdev)	49.7 (21.2)	1.2 (0.6)	0.08 (0.05)	9.8 (2.8)	0.01 (0.01)	0.57 (0.33)	6.6 (0.3)	1.3 (0.7)
West mean (stdev)	80.3 (23.4)	1.7 (0.7)	0.06 (0.01)	13.0 (3.3)	0.01 (0.025)	0.06 (0.08)	7.0 (0.2)	1.5 (0.9)
East median	44.2	1.1	0.07	9.1	0.01	0.54	6.6	1.2
West median	84.1	1.5	0.05	12.6	0.009	0.00	7.0	1.0

Median concentrations of ANC and NO_3^- for each Colorado wilderness area and ROMO show geographic differences reflective of atmospheric deposition, and bedrock composition (Figure 23). We plotted median values for east and west sides of all the wilderness areas that are bisected by the continental divide to see whether similar patterns existed outside of ROMO. In addition to ROMO, lakes were sampled on east and west sides of the Mount Zirkel, Indian Peaks, Weimenuche, and Holy Cross wilderness areas.

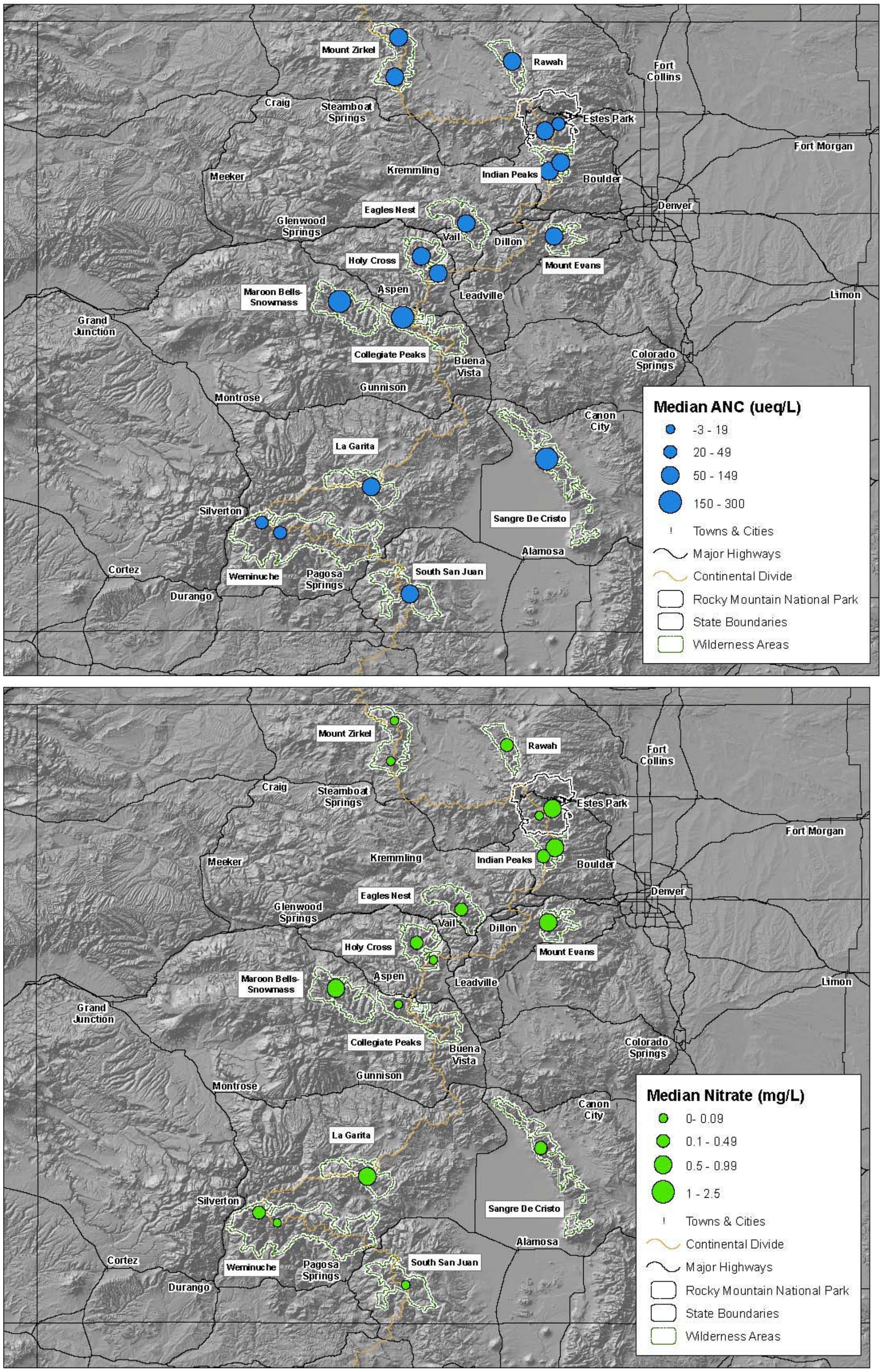


Figure 23. Median concentrations of ANC and NO_3^- from wilderness and national park lakes. Larger symbols depict higher concentration values. Medians were calculated across all sites in a park or wilderness boundary.

The lowest median ANC values (20-49 $ueqL^{-1}$) were found in sampled lakes from the east side of ROMO and on both sides of the divide in the Weimenuche. Other than ROMO, however, there was no difference in ANC based on location east or west of the continental divide. Higher NO_3^- concentrations, however, appeared to be geographically clustered closer to source areas. The highest sampled median lake NO_3^-concentrations occurred in the Colorado Front Range east of the continental divide in ROMO, Indian Peaks, and Mount Evans wilderness areas, as well as Maroon Bells-Snowmass and La Garita wilderness areas. The lowest (<0.1 mgL^{-1}) median NO_3^- concentrations in lakes of Mt Zirkel (east and west), South San Juan, Collegiate Peaks, Holy Cross (east), Weimenuche (east), and the west side of ROMO indicate the end-member median reference condition for alpine lakes is ≤0.1 mg $NO_3^-L^{-1}$. These data again suggest the MDC value is ≤0.1 mg $NO_3^-L^{-1}$.

Organic Contaminants and Metals

Measurable concentrations of manufactured contaminants, by definition, represent deviation away from the Historic Condition (HC), since they represent pollutants absent in natural conditions. The Western Area Contaminant Assessment Project (Landers et al. 2007) measured contaminant levels in select sites in western national parks, including Rocky Mountain, and compared concentrations across parks and within parks geographically and by elevation. The concentrations of contaminants in snow, air, vegetation, fish, and lake sediments were measured near or in one east-side lake (Mills Lake) and one west-side lake (Lone Pine). Endosulfans, dacthal, and mercury fluxes to snow were higher in ROMO than other western parks. The flux of dieldrin to snow was also higher at Mills Lake than elsewhere, possibly reflecting re-emission from contaminated soils in Denver where it used to be manufactured (Usenko et al. 2007).

An MDC for mercury was assessed by Yeardley et al. (1998) for 167 lakes in the northeastern U.S. These authors related the concentrations of methylmercury (MeHg) in fish tissue to critical loads for piscivorous birds and mammals, as well as to the fish themselves. Critical loads were defined from the literature as tissue concentrations that begin to pose a consumption risk. The human health critical value was 0.2 μg $g^{-1}$for MeHg. A critical value of 0.1 μg g^{-1}implies a risk to piscivorous mammalian wildlife populations, 0.02 μg g^{-1} for MeHg implies a risk to piscivorous avian populations (Yeardley et al. 1988). Based on the most conservative estimate 0.02 μg g^{-1} MeHG, fish tissue mercury concentrations in ROMO that range from 0.03 to 1.10 μg g^{-1} are greater than the minimally disturbed condition, the MDC. Mercury concentrations were higher in older than in younger fish in both Mills and Lone Pine Lakes, and endosulfans and dacthal were fairly high in fish tissue. Mercury concentrations exceeded contaminant health thresholds for otter, mink, and kingfishers in both lakes. Methymercury availability will vary between lakes depending on the surrounding landscape, so more sampling is necessary in order to evaluate the consumption risk from fish to humans and wildlife parkwide, but the measured concentrations from Mills and Lone Pine Lakes serve as a warning. Evidence of endocrine and reproductive disruption in several park lakes is present. Estrogen-responsive proteins were found in male trout from four out of nine lakes, and poorly developed testes and/or intersex male trout were also found in five out of nine lakes. Dieldrin in all fish exceeded contaminant health thresholds for recreational fishermen in some lakes.

Historical Reconstructions of Acid Neutralizing Capacity

DayCent-Chem model results since 1900 in Andrews Creek in Loch Vale Watershed on the east side of the park suggest ANC has fluctuated with time in response to increases and decreases in sulfate deposition (Figure 24). The simulations suggest ANC was about 65 µeq $L^{-1}$for this alpine stream in 1900 and declined to its lowest value of less than 20 µeq L^{-1} corresponding with the peak SO_4^{2-} deposition in 1969, and began to recover after that, coincident with the implementation of the Clean Air Act of 1970. Peak N deposition amounts occurred in 1994-1995, coincident with another decline in ANC. Model results suggest there has been a loss of approximately 26 µeq L^{-1} of ANC from Andrews Creek since 1900. This value is similar to that proposed by Gibson et al. (1983), who calculated the loss of ANC in Rocky Mountain National Park of about 18.5 µeq L^{-1} based on the difference between estimated ANC from base cation concentrations and measured values from a sample for 40 lakes in the park. While one MDC value for ANC cannot be set for ROMO, since ANC varies due to many factors, it appears the current ANC values are lower than the MDC by approximately 18-26 µeq L^{-1}.

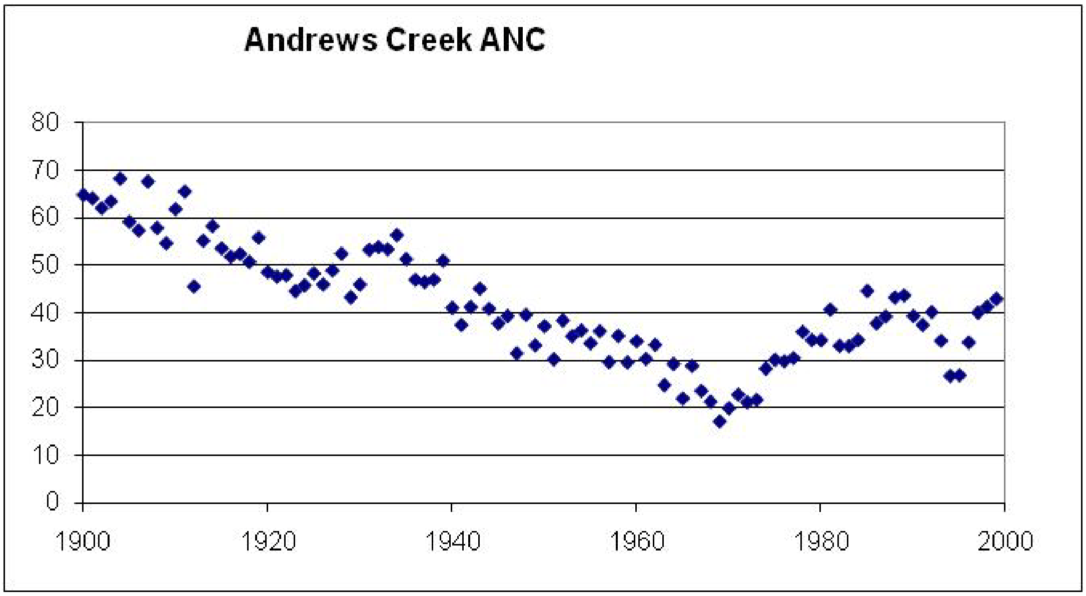


Figure 24. Modeled changes in Andrews Creek Acid Neutralizing Capacity (ANC, µeq L^{-1}) over time using the DayCent-Chem model and reconstructed wet plus dry N and S deposition values.

Uses and Limitations

Alpine lakes in protected national parks and wilderness areas should represent some of the least disturbed environments in the world. Anthropogenic disturbance has three likely sources: atmospheric deposition, climate change, or direct human manipulation, such as by introducing or removing species. Our evaluation of water quality for ROMO lakes suggests some chemicals have exceeded the minimally disturbed condition, the MDC. For some others, we were unable to determine whether their concentrations have changed with time; the values reported here can be considered a starting point from which to evaluate and interpret future concentrations. All of the inorganic values reported here are well below water quality guidelines for drinking water standards, and their concentrations are addressed in terms of their possible influence on non-human organisms such as algae, zooplankton, and fish.

Trends in Atmospheric Deposition

Atmospheric deposition is a major driver of environmental change in ROMO, warranting continued monitoring and assessment of its constituents. There has been a decrease in wet and dry deposition of SO_4^{2-} over time, and a corresponding decrease in precipitation acidity. This indicates a reduced risk to park biota from acid rain. An increase in Ca^{2+} deposition at both Beaver Meadows and Loch Vale may also have contributed to the decreased annual acidity trend. Calcium is an indicator of dust, and evaluation of Ca^{2+} concentrations over time can be indicative of changing climates or land use change.

Inorganic N, and its components NO_3^- and NH_4^+, has increased over time at both precipitation monitoring sites, and has been strongly related to ecological and water quality changes in ROMO. The Colorado Nitrogen Deposition Reduction Plan calls for continued monitoring in order to evaluate whether wet N deposition is decreasing according to the glidepath toward achieving deposition at or below the critical load of 1.5 kg N ha^{-1} yr^{-1} by 2035.

Potential for acidification from atmospheric deposition

ANC values are lower than the MDC by approximately 18-26 µeq L^{-1}. The DayCent-Chem model suggested pH declined from 6.9 in 1900 to 6.6 100 years later (data not shown). From the lake survey results, east-side lakes had an average pH of 6.6, while the west-side lakes averaged pH 7.0, similar to the modeled results. While confidence in the absolute loss of ANC and pH from east-side lakes is lower than if a decline in values over time had been measured, it appears there has been a reduction in buffering from acidic deposition over time. Research and policy recommendations from the National Acid Precipitation Assessment Program use the following guidelines for interpreting levels of ANC and pH (Charles 1991):

- ANC of 50-100 ueq/L, considered acid sensitive but capable of supporting healthy biota
- ANC $<$ 50 ueq/L, sensitive to acidification, potential effects to biota
- ANC $<$ 20 ueq/L, can be episodically acidic, sub-lethal or lethal affects on biota
- ANC $<$ 0 ueq/L, can be chronically acidic, lethal effects on many biota.

A number of species, especially trout and macro-invertebrates, cannot survive, reproduce or compete in acidic waters (harmful effects can begin at pH $<$ 6).

ROMO lakes currently have ANC values below 100 µeq L^{-1}, and east-side lakes have mean values of 50 µeq L^{-1}. ANC values should be monitored in conjunction with atmospheric deposition chemistry, because the granitic bedrock that underlies the park, combined with the modeled historic loss already of buffering capacity, suggested east-side lakes are close to ANC values below which there could be episodic acidification and lethal or sublethal effects to fish or invertebrates.

Potential for eutrophication from atmospheric N deposition

The regional comparison of lake chemistries suggests the reference condition for NO_3^- was ≤0.1 mg L^{-1}. Nitrate concentrations were higher than these values in east-side sampled ROMO lakes (mean NO_3^-= 0.57; median NO_3^-=0.54), compared with west-side lake concentrations (mean NO_3^-=0.03; median NO_3^-=0.00). The spatial comparison is in keeping with nitrogen saturation theory proposed by Stoddard in 1994 that suggested no measurable stream or lake NO_3^- should be present where atmospheric N deposition was not elevated. Bergström et al. (2005) and Bergström and Janssen (2006) also found that lakes receiving extremely low N deposition had <0.024 mg L^{-1} NO_3^-, whereas there was a direct and strong correlation of increasing NO_3^- concentrations in lakes receiving increasing N deposition in Europe and North America. Studies by Elser et al. (2009a, 2009b), which included lakes in ROMO, found a clear relation between atmospheric N deposition and the nitrogen to phosphorus ratio. Increasing N deposition leads to increased lake NO_3^- and algal assemblages that thrive on high N availability. These phosphorus deficient algae are poor food quality for zooplankton, and may eventually alter nutritional dynamics up the food chain to fish (Elser et al. 2009a, 2009b). Research in ROMO has already established a switch of algal assemblages toward dominance by disturbance species that thrive in high N waters (Baron et al. 2000, Baron 2006); research into whether zooplankton populations and assemblages have indeed been altered, and research into whether algal diversity has decreased as a result if increased N in lakes are needed.

If the reference condition for $NO_3^-$is $\leq$0.1 mg L^{-1}, then select lakes on the east side of the Front Range in ROMO, Mount Evans, and Indian Peaks have values that are in excess of the reference, as do lake chemistries from several other sites in wilderness areas in Colorado, Utah, and Idaho. Particularly for the Front Range lakes, this is consistent with recent studies correlating proximity to source areas for N emissions with elevated lake nitrate concentrations (Baron et al. 2000, Baron et al. 2004, Burns 2004, Nanus et al. 2008), and with a hindcasting exercise that showed increasing wet N deposition corresponded with increased algal productivity and species dominance in east-side ROMO lakes (Baron 2006).

Changes in weathering products with time

Sulfate, chloride, and calcium are chemical species that can weather from bedrock and also have an atmospheric deposition source. Conductivity is a good general measure of how dilute or concentrated water are. Changes in values of these solutes over time, if correlated with changes in measured atmospheric precipitation, can indicate changes in inputs of pollutants such as SO_x, or dust. Increased concentrations can also indicate glacier melt, and a recent study in Loch Vale, as well as other mountain regions, reported increased weathering products from recent warm summer temperatures (Baron et al. 2009). For all these compounds, time series, either in current monitoring programs or from paleolimnological reconstructions, may be the only way to determine if concentrations are changing. Except for increases in SO_4^{2-}, which leads to acidification, effects of increasing concentrations of other salts are not likely to alter lake biota. Perhaps the most important reason to monitor these chemicals is as indication of other regional or global changes occurring from land use, climate change, or emissions of pollutants.

Contaminants

Soluble organic chemicals and heavy metals derived from agricultural and industrial practices were not present in Rocky Mountain waters prior to their societal applications (Table 21). For these atmospherically-deposited compounds, any measurable concentration represents a deviation away from the historic condition, the HC. The WACAP study provided a comparison of contaminant concentrations across select lakes in western national parks, and ROMO has lower concentrations of some elements than other park lakes, and higher concentrations of others (Landers et al. 2007, Usenko et al. 2007). As with nitrate, higher concentrations of mercury and dieldrin were found in east-side sites than west-side, reflecting east-side source areas. A conclusion of the WACAP study was that total soluble organic chemical concentrations in snow were highest in the Rocky Mountain parks of ROMO and Glacier, and Sequoia NP, and these parks also had higher concentrations of contaminants in fish tissue and lake sediments. Some of these concentrations exceed critical values for wildlife and piscivorous birds. Evidence of endocrine and reproductive dysfunction in fish and harmful concentrations of dieldrin are cause for continued monitoring of contaminants and their toxicological effects. Monitoring, too, will be important for providing public notice of health hazards.

Table 21. Water Quality Thresholds (see text for full explanation)

Measure	Minimally Disturbed (MDC) or Historic (HC) Condition	Current Mean ROMO Condition	Data Quality	Confidence	Level of Concern
Lake pH	6.5-7.5	6.6 (east) 7.0 (west)	Good	Moderate	High
Lake ANC (µeq/L)	80-100	50 (east) 80 (west)	Good	Moderate	High
Lake ammonium (mg L^{-1})	Below detection limits	0.01 (east) 0.01 (west)	Good	Moderate	High
Lake nitrate (mg L^{-1})	≤0.1	0.57 (east) 0.06 (west)	Good	High	High
Lake sulfate (mg L^{-1})	0.2-109.0 (all lakes)	1.3 (east) 1.5 (west)	Good	High	High
Lake chloride (mg L^{-1})	0.03-1.16 (all lakes)	0.08 (east) 0.06 (west)	Good	Moderate	Low
Lake calcium (mg L^{-1})	0.1-43.9	1.20 (east) 1.65 (west)	Good	Moderate	Low
Lake conductivity (µS/cm)	2.2-341.8	9.8 (east) 13.0 (west)	Good	High	Low
Fish Mercury (µg g^{-1})	<0.01 fish	0.03-0.09 (east) 0.04-1.10 (west)	Good	High	High
Dieldrin (ng g^{-1})	0.0 snow; fish	>1.0 snow	Good	High	High
DDT (ng g^{-1})	0.0 fish	≥4.0 fish	Good	High	High

Overall our general estimate is that this is an area of *high concern*. Our level of confidence for this indicator is *high amount of agreement* and *moderate amount of evidence*. We rate it this way because there is strong literature and data support for cause and effect relationships between lake chemistry and atmospheric deposition.

Summary: Air and climate – Condition of Alpine Lakes and Atmospheric Deposition

What: Measures atmospheric deposition of nutrients and pollutants in high elevation lakes.

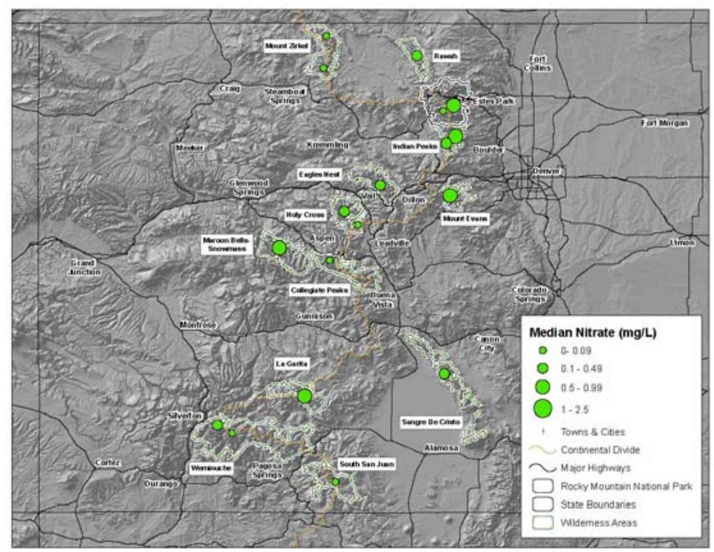
Why: High elevation lakes are bellwethers of ecological change and the extent of human-caused disturbance.

Stressors: Land use change, climate change

Confidence: High degree of concern; moderate evidence, high agreement

Atmospherically-deposited nitrogen has caused east-side ROMO lakes to have higher than background nitrate concentrations and lower than expected acid-neutralizing capacity (ANC). East-side concentrations of dieldrin and DDT are also elevated, while west-side mercury in fish tissue is at or above concentrations that are harmful for some birds and mammals. West-side nitrate and ANC are consistent with reference conditions, and lake pH and chemical concentrations of calcium, chloride, sulfate, ammonium for all ROMO lakes are consistent with reference conditions.

Measure	Reference Condition	Current condition	Confidence	Level of Concern
Lake pH	6.5-7.5	6.6 (east) 7.0 (west)	Moderate	High
Lake ANC	80-100 µeq L^{-1}	50 µeq L^{-1}(east) 80 µeq L^{-1}(west)	Moderate	High
Lake ammonium	Below detection limits	0.01 mg L^{-1} (east) 0.01 mg L^{-1} (west)	Moderate	High
Lake nitrate	≤0.1 mg L^{-1}	0.57 mg L^{-1} (east) 0.06 mg L^{-1} (west)	High	High
Lake sulfate	0.2-109.0 mg L^{-1} (all lakes)	1.3 mg L^{-1} (east) 1.5 mg L^{-1} (west)	High	High
Lake chloride	0.03-1.16 mg L^{-1} (all lakes)	0.08 mg L^{-1} (east) 0.06 mg L^{-1} (west)	Moderate	Low
Lake calcium	0.1-43.9 mg L^{-1}	1.20 mg L^{-1} (east) 1.65 mg L^{-1} (west)	Moderate	Low
Lake conductivity	2.2-341.8 µS cm^{-1}	9.8 µS cm^{-1} (east) 13.0 µS cm^{-1} (west)	High	Low
Fish Mercury	<0.01µg g^{-1}	0.03-0.09 µg g^{-1} (east) 0.04-1.10 µg g^{-1} (west)	High	High
Dieldrin	0.0 ng g^{-1} snow	>1.0 ng g^{-1} snow	High	High
DDT	0.0 ng g^{-1} fish	≥4.0 ng g^{-1} fish	High	High



*Additional data sources: Western Airborne Contaminants Study (WACAP 2008).

4.2.2 Water: Extent and Connectivity of Wetland and Riparian Areas

Authors: David M. Theobald and John B. Norman, III

Description/Purpose

This indicator measures the extent and connectivity of riparian areas and wetlands along the hydrologic network of the park. Fragmentation of habitat in terrestrial systems is widely recognized to be one of the primary aspects of change to natural systems. Fragmentation also occurs in freshwater systems, and parallels between terrestrial and freshwater systems recently have been drawn (Wiens 2002). Here we are particularly concerned about fragmentation and connectivity longitudinally (up and down along the stream network), although there can also be lateral and vertical fragmentation as well.

The modification of hydrologic regimes by dams has been studied in particular, and Poff et al. (2007) found that regional homogenization can occur through modification of both magnitude and timing of both high and low flows that are a critical characteristic of natural river systems. Human-made impoundments (reservoirs and ponds) have also been shown to harbor invasive aquatic species and serve as "stepping stones" for the spread of exotic organisms (Johnson et al. 2008). The crossing of streams with roads is another commonly used indicator of likely fragmentation or alteration of flow regimes, though we did not include these in our analyses because we lacked detailed data about the location and type of bridges and culverts, which is needed to conduct a more comprehensive analysis (e.g., USDA 2008).

Within the park, there are a number of natural barriers, such as waterfalls, which affect the movement of aquatic organisms, such as the upstream movement of fish. These natural barriers have been important in protecting upstream organisms from exotic fish encroaching from below. Also, there are a number of introduced human modifications—including a number of ditches and dams. These barriers in the park alter hydrologic flows and likely fragment the freshwater systems along the streams as well as wetland and riparian communities (Table 22; Woods 2000).

Table 22. Barrier features that were identified by park resource managers that alter movement and connectivity along the freshwater system in the park.

Source	HUC 8 basin	Features
Natural barriers	Colorado River	Granite Falls, Cascade Falls (Tonahutu Creek) Adams Falls, unnamed Falls (East Inlet)
	Big Thompson	Lost Falls (North Fork) Chasm Falls & unnamed Falls (Fall River) Fern, Marguerite, and Grace Falls (Fern Lake Canyon) Alberta, Glacier, and Ribbon Falls (Glacier Creek)
	St. Vrain	Columbine, Copeland, and Ouzel Falls and Calypso Cascades
Human-made barriers	Colorado River	Grand & Specimen Ditches (crosses 8 streams) Eureka Ditch (restored), Big Meadows (restored)
	Big Thompson	Lily and Sprague Lakes (dam) Lawn Lake (restored) McGraw Ranch, Moraine Park (ditch, restored)
	St. Vrain	Inlet Ditch to Copeland Lake (dam) Bluebird, Pear, and Sandbeach Lakes (restored)

Water diversions also negatively affect willow seedling establishment in riparian areas of ROMO (Woods and Cooper 2005). In addition, wetlands adjacent to alluvial fans are vulnerable to upstream water diversions, such as the Grand Ditch that divert water from Lost Creek (Figure 25; Woods et al. 2006) and other tributaries that often impact fens below. As an example of these fragmenting features, Cooper et al. (1998) documented the modification of the hydrologic regime from a ditch and the subsequent restoration of Big Meadows fen along the Tonahutu Creek.

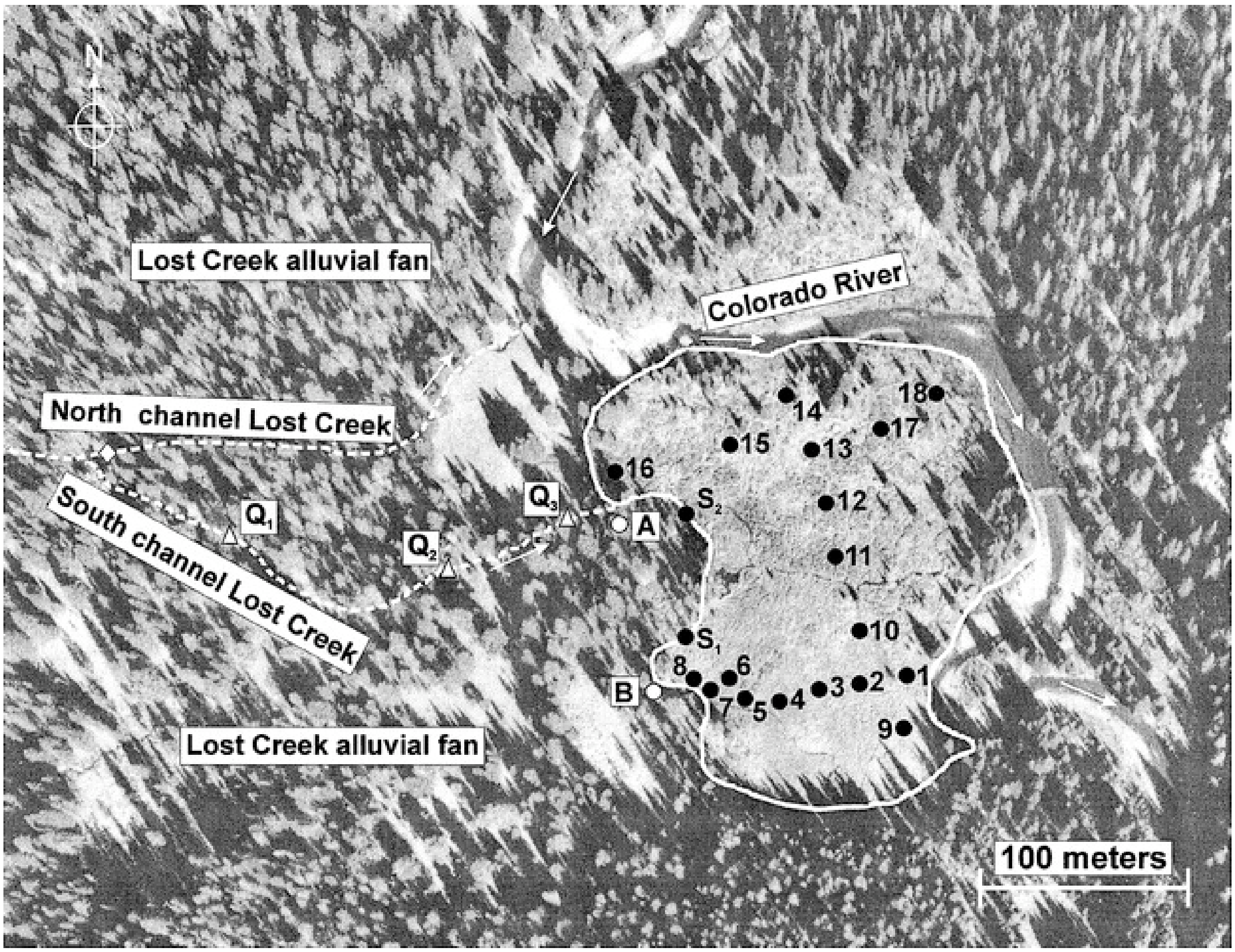


Figure 25. Aerial photograph of Woods et al. (2006) Lost Creek study site. Stream-gauging stations are depicted by Q1, Q2, and Q3 (triangles), springs S1 and S2, monitoring wells and piezometer nests 1 to 18 (black circles), piezometers A and B (white circles), and the dam constructed in 1998 to divert water into the south channel in 1998 (diamond). The solid white line is the wetland boundary, and the dashed lines indicate the north and south channels of Lost Creek. Arrows indicate the direction of stream flow in Lost Creek and the Colorado River. The beaver dam in the Colorado River east of the wetland was not present during the study.

Approach/Methods

Our overall approach for this indicator was to identify riparian vegetation zones along the hydrology network, and then to identify features that are considered barriers to movement (connectivity) along the freshwater system. These included both natural and human-made barriers. We identified the location of riparian or wetland features by finding patches of vegetation from those cover types identified as either riparian or wetland in the ROMO vegetation dataset (Table 23; Figure 26; Salas et al. 2005). We then removed those patches that did not intersect or touch the 1:24K hydrology stream network, so as a result most fens were not included in this analysis. Our attention towards those patches that lie along the hydrologic network reflects our focus on surface water connectivity; although there are many wetlands that are also strongly influenced by groundwater conditions, we excluded these from our analysis. Also note that there is an ongoing inventory of wetlands in the park (D. Cooper, personal communication), but these data were not available in time for this study.

Table 23. Land cover types identified as wetland and/or riparian types in the ROMO vegetation map (Salas et al. 2005).

Riparian Cover Class	COMMON_MAP classes	Total area (ha)	Riparian area (ha)
Alpine Wetland	Herbaceous Wetland Sub-alpine / Alpine – Meadow (100%)	8654	6804
Cottonwood	Cottonwood (100%)	31	28
Herbaceous Wetland	Herbaceous Wetland Cross Zone – Marsh (2%) Herbaceous Wetland Cross Zone – Wetland (98%)	2229	2852
Riparian Aspen	Riparian Aspen (100%)	370	293
Riparian Mixed Conifer	Riparian Lower Montane Mixed Conifer < 8500 ft (10%) Riparian Lower Montane Mixed Conifer > 8500 ft (85%) Blue Spruce (5%)	3939	3592
Shrub Riparian	Shrub Riparian Cross Zone < 9600 ft (45%) Shrub Riparian Cross Zone > 9600 ft (55%)	2906	2607
Shrub Upland Alpine	Shrub Upland Alpine (100%)	1838	1374

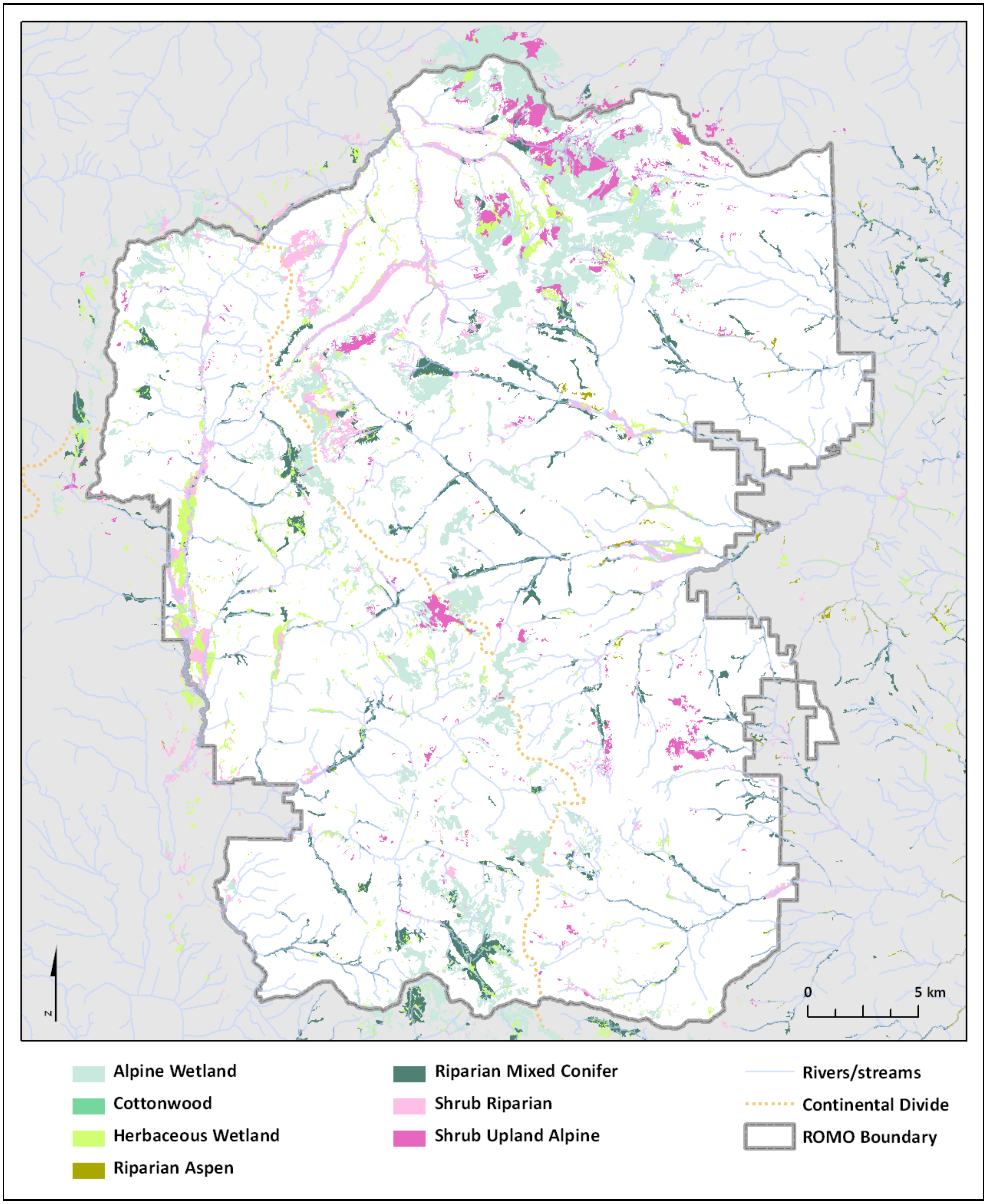


Figure 26. Vegetation types identified as wetland and/or riparian in the ROMO vegetation dataset. These exclude fens and other groundwater-dominated wetlands.

We generated a network representation of the hydrologic network in GIS, using the Functional Linkage of Watersheds and Streams (FLoWS) tools (Theobald et al. 2005). We used the 1:24K blue-line hydrology (updated to include recent modifications to the location of streams and small ponds), and processed the GIS data so that stream lines were topologically correct, enabling routing of flow along the network. See Technical Appendix 2 for a more detailed description of the methods.

We computed two types of measures of freshwater connectivity. First, the patch area was computed for each stream reach and then accumulated downstream. Downstream accumulation means that the a stream reach is followed to the next reach downstream that it connects with, and the various values, such as area of riparian vegetation, is then summed as one works down the network. If a barrier was encountered, then the accumulated area was reset to 0. High values indicate large patches of wetland/riparian areas that are longitudinally connected. Low values indicate small patches and/or disconnected (fragmented) riparian corridors. Second, we computed a measure that quantifies aspects of the sub-networks that form between barriers. Sub-networks are the pieces of the full hydrologic network that are created when barriers "cut" them into smaller networks that are connected within a sub-network, but isolated from other sub-networks. This measure differs from the downstream accumulation measure in that it characterizes connectivity without regard to direction (i.e. upstream or downstream), and so might be a better measure for understanding connectivity from a mobile organism perspective (e.g., a fish or beaver that can swim up or down stream). For each sub-network, the total stream length (km), the total wetland/riparian area (ha), and the average wetland/riparian area (ha per stream km) was computed. Natural barriers were assumed to disrupt upstream movement of fish in particular, but were assumed to not modify significantly downstream movement of water flow or fish. Human barriers were assumed to strongly disrupt (break) both upstream and modify downstream flow of water.

Reference Condition

There are two measures associated with this indicator: 1) average connected stream length, and 2) average area of connected riparian/wetlands. The reference condition for these measures is based on "minimally disturbed condition" (MDC); that is, streams without human-made barriers. It is established based on interpretation of historic condition—in this case, the absence of human-made barriers. To compare the values of these measures, we developed a series of scenarios that allow us to make inferences. To do this, we examined how the connectivity of the riparian and wetland system has likely changed over the time that constitutes our three scenarios: "natural" (to approximate natural conditions), 1900-1990s (historic), and current.

The *"natural"* connectivity scenario assumes that the natural features that cause barriers to fish movement (upstream only) are included, but no other human-made features such as dams or ditches interrupt the connectivity of the freshwater system. The *"historic"* scenario (1900-1999) approximates the situation where ditches and diversions were at their maximal extent. This hydrological system includes the Grand Ditch. It also includes the Eureka Ditch, which diverted water from Tonahutu Creek on the west slope to Spruce Creek on the eastside (this was filled in 1996). Harbison Ditch diverts water from Tonahutu Creek into Columbine Lake and is still operating. A few miscellaneous irrigation/drainage ditches include: Big Meadows (west side) and Beaver Meadows (east side), and Moraine Park (eastside); Holzwarth Ranch (diversion gate next to bridge that crosses the Colorado River); McGraw Ranch Ditch from Cow Creek to small pond. Dams that impound water include Lily, Sprague, and Copeland Lakes; Bluebird, Sandbeach, Pear, and Lawn Lake have been restored back to "natural" lake levels. The "current" connectivity scenario includes all natural barriers, but incorporates the removal of some human-made barriers, notably the Big Meadows, Eureka, and Upper Beaver Meadows ditches, and as outlined in Table 24.

Table 24. Three scenarios reflecting natural, historic, and current conditions that affect connectivity between wetland and riparian areas along stream corridors.

Scenario	Hydrologic Features
"Natural"	• Natural hydrology in 1:24K NHD • Natural barriers
Historic (1900 – 1990)	• All hydrological features in 1:24K NHD • Natural barriers • Ditches: Grand, Eureka, Harbison, Big Meadows (east & west), Holzworth Ranch, Cow Creek • Dams: Lily, Sprague Copeland, Bluebird, Sandbeach, Pear, Lawn
Current	• All hydrological features in 1:24K NHD • Natural barriers • Ditches: Grand, Harbison, Cow Creek • Dams: Lily, Sprague Copeland

Note that we are using the same vegetation map for all three scenarios, so we are unable to include differences between historical and current extent and location of wetlands and riparian areas.

Results/Discussion

Under "natural" conditions, the major expanses of connected wetland/riparian vegetation included: Kawuneeche Valley (Colorado River) and East Inlet on the west side of the park and Forest Canyon (along the Big Thompson River), Fall River, and Cache la Poudre/Hague Creek on the eastside (Figure 27). The numerous different watersheds and natural barriers along streams generate 94 unique sub-networks of streams (Table 25).

Table 25. Results for the connected hydrologic sub-networks, created by human-barriers fragmenting the network (and incorporating natural barriers as well), averaged by 12 digit HUC for the "natural", historic, and current scenarios. The average wetland/riparian density is a measure of the sum of the riparian patches that are connected, divided by the stream length (km) that connect each sub-network.

Scenario	No. sub-networks	Average stream length (km)	Average wetland/riparian area (ha)	Average wetland/riparian density (ha/km)
"Natural"	94	11.4 (SD=36.6)	146.6 (SD=410.2)	11.7 (SD=17.8)
Historic	123	8.7 (SD=22.3)	112.1 (SD=288.6)	11.5 (SD=19.7)
Current	111	9.6 (SD=26.2)	124.2 (SD=322.6)	11.5 (SD=17.4)

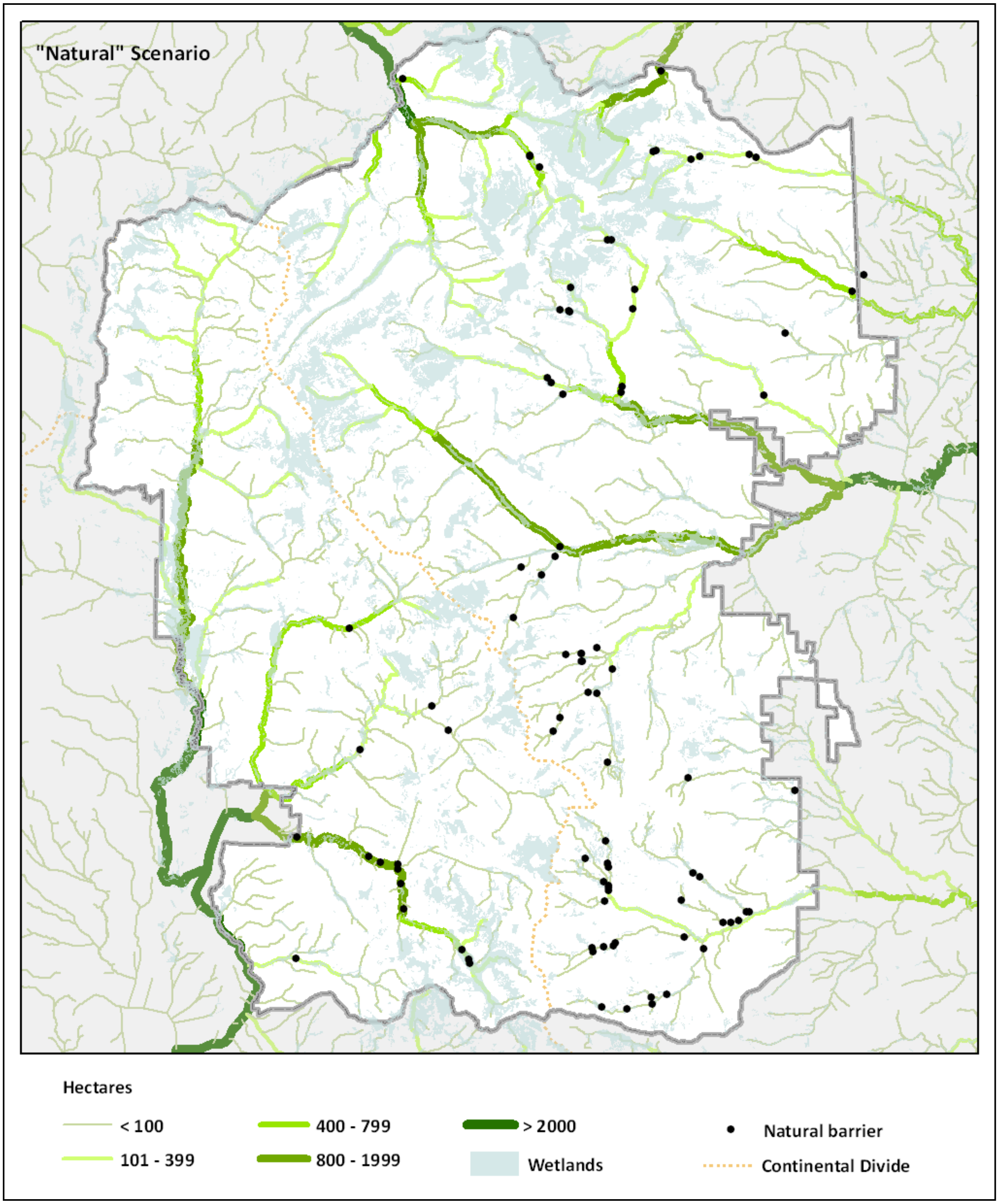


Figure 27. Hectares of riparian and wetland systems accumulated downstream, reflecting the “natural” scenario.

Disruptions in connectivity due to human-made barriers/diversions occurred in the 1900s-1990s, from the Grand Ditch as well as low in the Kawuneeche Valley (near Bowen Gulch), Tonahutu Creek, and the Poudre/Hague Creek in the north part of the park and along the North St. Vrain (Figure 28). This resulted in 123 sub-networks (Table 25), but more importantly caused a 25% reduction in both the average stream length of connected sub-networks and the average riparian/wetland area that was connected—from 147 to 112 ha.

The current scenario shows some improvement in the connectivity of the freshwater system (Figure **29** 29). More recently (2009), with a number of restoration activities that have taken place in the park, additional improvements in the connectivity of the freshwater system have been made, particularly as the major disruption along the Kawuneeche Valley was removed, as well as on Tonahutu Creek. Both the average stream length (8.7 to 9.6 km) and average wetland/riparian area connected (112.1 to 124.2 ha) have increased.

Figure 30 shows a comparison of the *change* in connectivity between the “natural” scenario and the historic scenario and the *change* in connectivity between the “natural” scenario and the current scenario. This shows that there have been large increases in connectivity as a result of the restoration activities reflected in the *current* scenario. However, high elevation barriers along the Grand Ditch remain important in reducing connectivity. Also, the watershed of Tonahutu Creek remains fragmented.

The most extensive riparian/wetland systems historically were along the Kawuneechee Valley and the Cache la Poudre River. The Kawuneechee system remains highly modified, with seven tributaries having flow modified by ditch diversions.

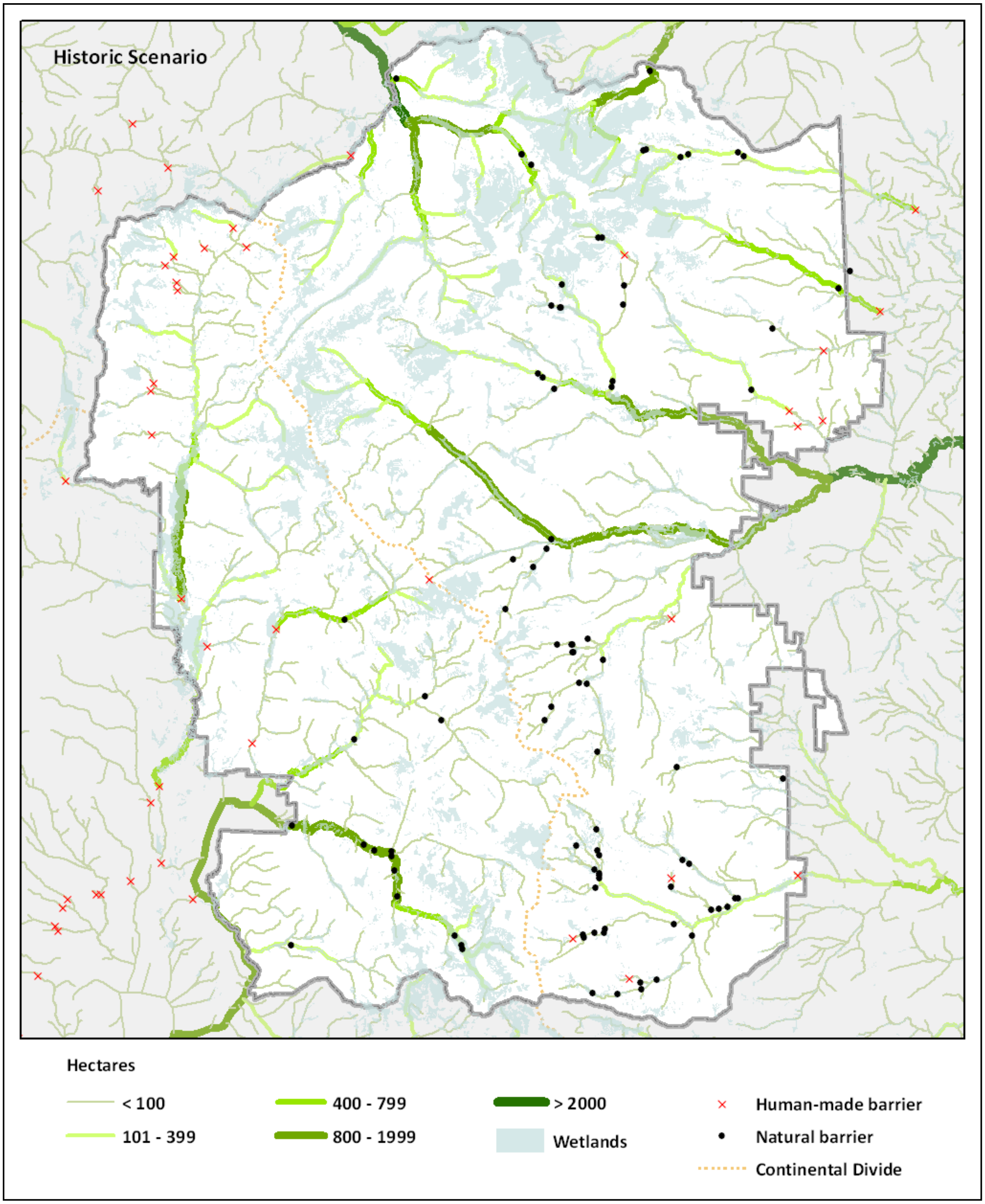


Figure 28. Hectares of riparian and wetland systems accumulated downstream, reflecting the *historic* (1900-1990s) scenario. Natural barriers that disrupt downstream flow are shown as black dots; human-made barriers are shown as red crosses.

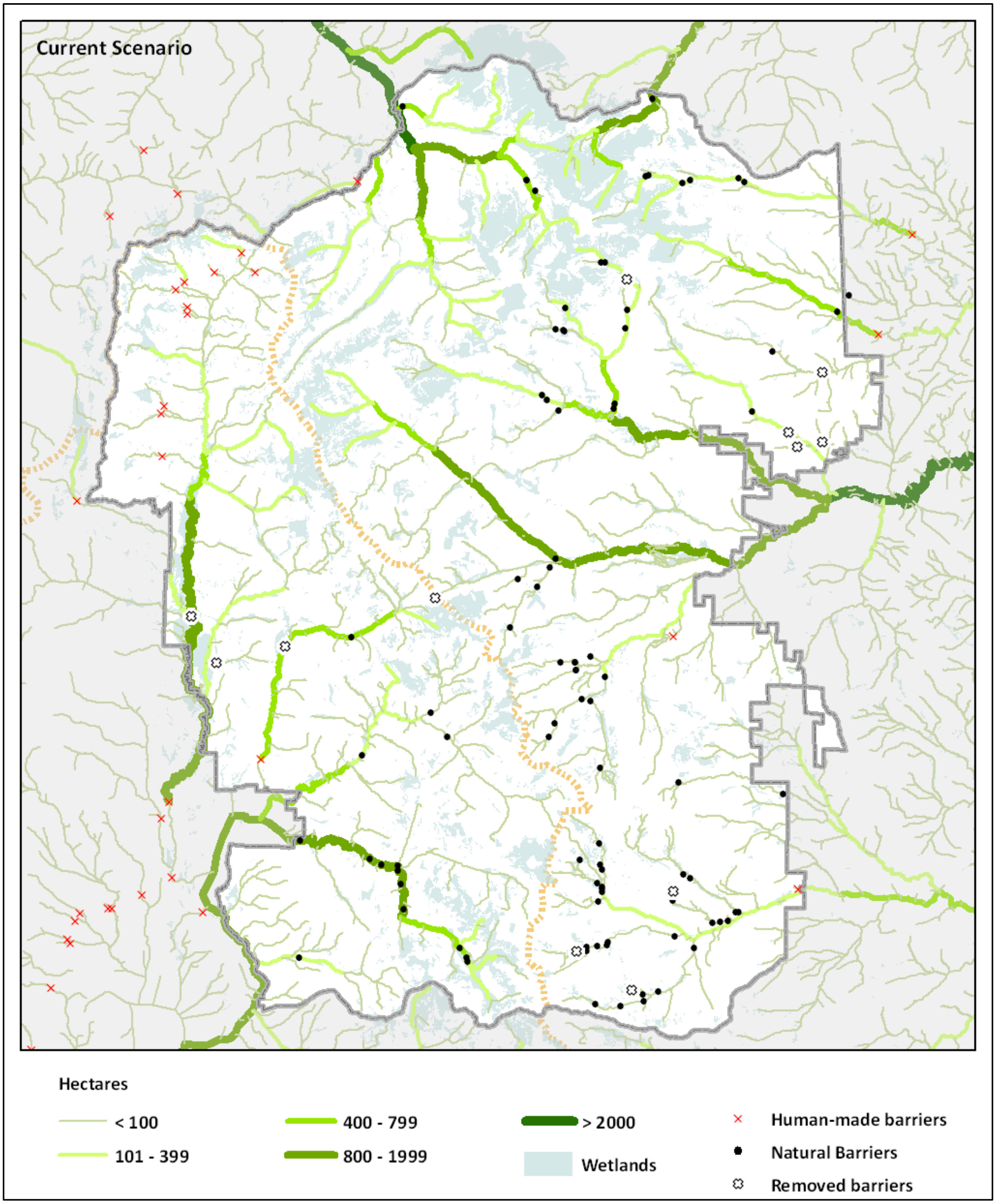


Figure 29. Area of riparian and wetland systems accumulated downstream, reflecting the current scenario. Natural barriers that disrupt downstream flow are shown as black dots, human-made barriers are red crosses and barriers that have been removed are hollow crosses.

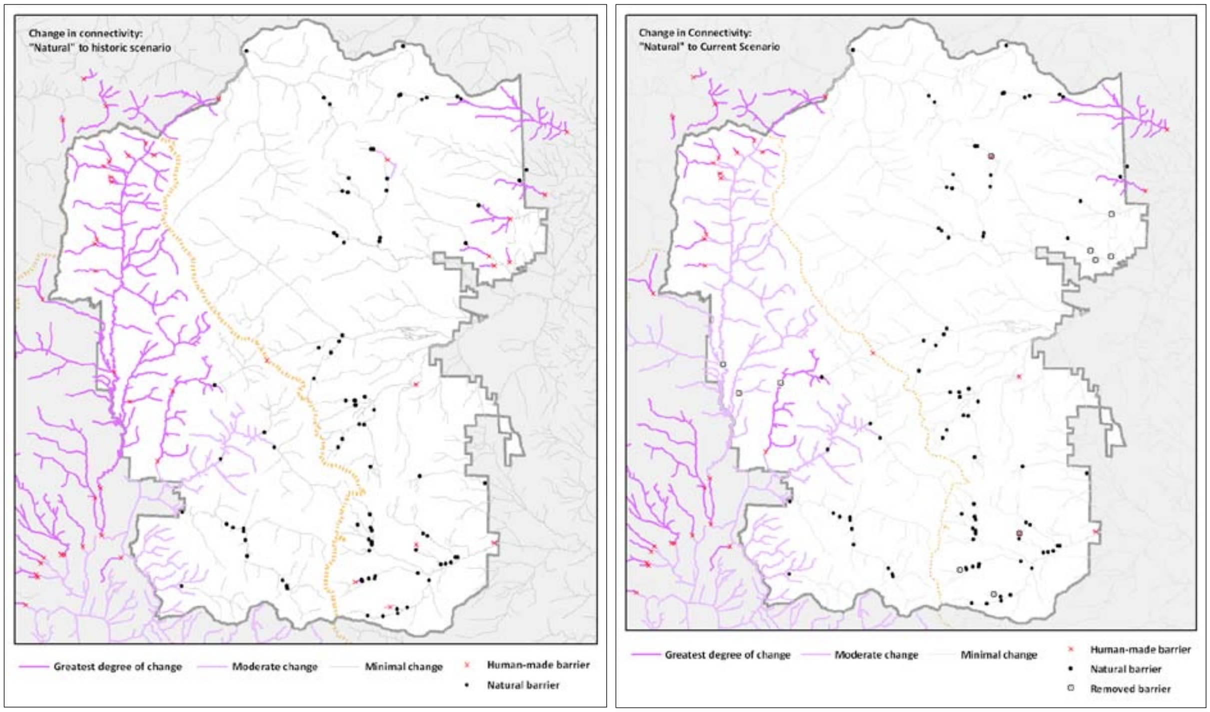


Figure 30. Change in connected stream systems between "natural" scenario and historic scenario, and between "natural" scenario and current scenario.

The most extensive riparian/wetland systems historically were along the Kawuneechee Valley and the Cache la Poudre River. The Kawuneechee system remains highly modified, with seven tributaries having flow modified by ditch diversions. The flow modifications along the Cache la Poudre system occur lower in the hydrological system, near the park boundary.

We also provide cumulative distribution frequency graphs of these measures to compare the scenarios (Figure 31).

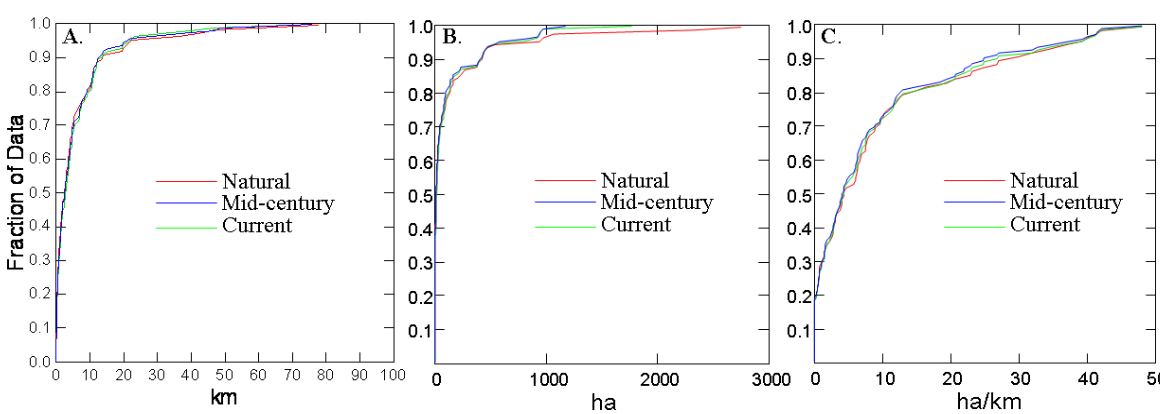


Figure 31. Graphs of cumulative frequency functions for total stream length (left), total riparian/wetland area (center), and average riparian/wetland area (right). This shows that roughly 80% of stream segments are about 10 km or less.

Figure **32** shows the percentage of each watershed that is in riparian/wetland vegetation.

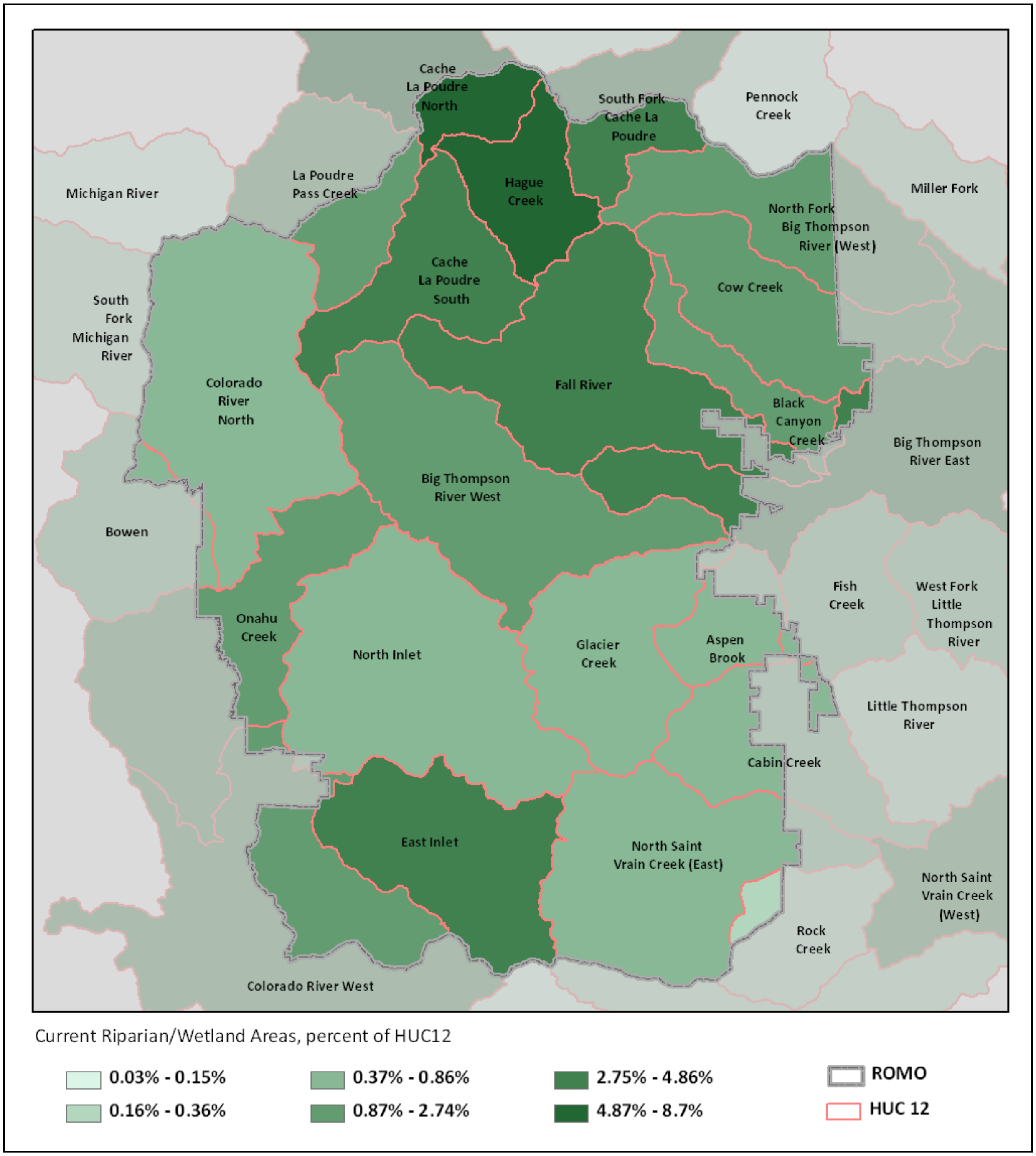


Figure 32. Percentage of each watershed (HUC-12) that is currently riparian or wetland vegetation.

Uses and Limitations

Overall, we believe that this indicator supports a *high degree of concern*, because of the importance of the riparian/wetland areas to the park, the extent and widespread disruption of the hydrologic processes in the park, and the adaptation of species to changing climate regimes will be impinged. We rank our level of confidence in this indicator as *moderate/low*. There is *moderate agreement* about the importance of maintaining hydrologic connection to ensure natural variability in the hydrograph and its importance for wetland and riparian ecosystems. There is a *low amount of evidence*. Currently there are few data points to make a comprehensive conclusion, but there is good field experience and guidance from experts that this is an important indicator.

Summary: Water - Extent and Connectivity of Wetland and Riparian Areas

What: Measures the extent and connectivity of riparian and wetlands along the hydrologic network.

Why: To understand potential impacts on riparian and wetland communities as a result of hydrologic fragmentation due to human barriers (e.g., dams, ditches)

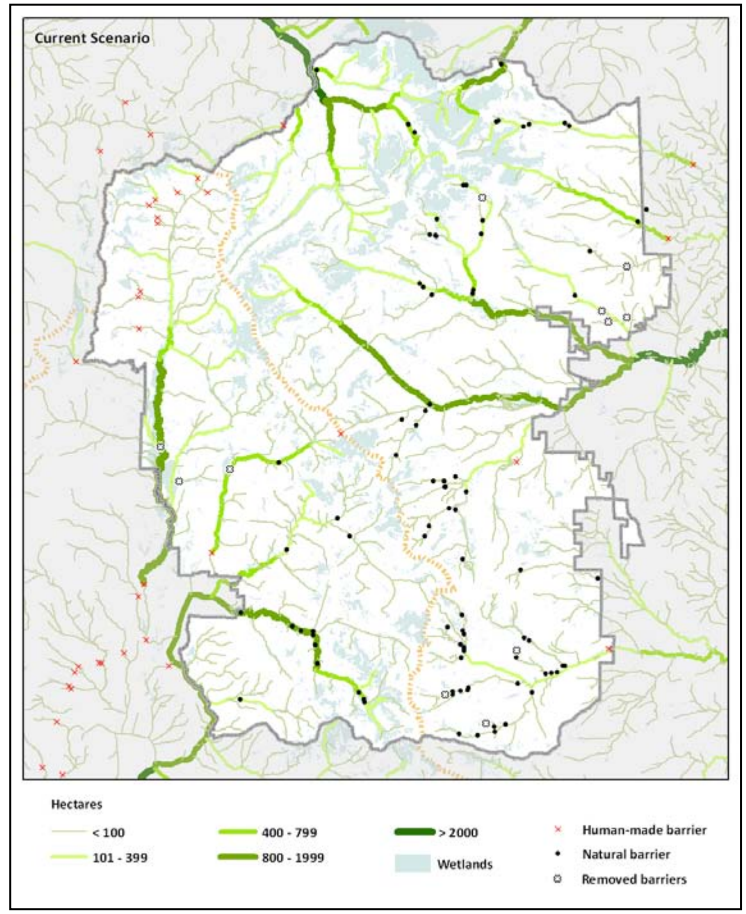
Stressors: Infrastructure, visitor use, climate change

Confidence: High degree of concern; low evidence, moderate agreement.

Restoration of four dams and four ditches has improved the connectivity of riparian and wetland communities somewhat from 1900-1990s conditions, but current conditions (shown right) remain substantially fragmented compared to "natural" hydrological conditions.

Measure	"Natural"	Historic (1900-1990)	Current
Average connected stream length (km)	11.4 SD=36.6	8.7 SD=22.3	9.6 SD=26.2
Average connected riparian/wetland area (ha)	146.6 SD=410.2	112.1 SD=288.6	124.2 SD=322.6

*As mapped in ROMO vegetation map (Salas et al. 2005) and 1:24K hydrology.



4.2.3 Biotic Integrity: Extent of Exotic Terrestrial Plants
Authors: David M. Theobald and John B. Norman, III

<u>Description/Purpose</u>
There is a growing concern in the park regarding the loss of habitat and the economic cost of controlling invasive exotic species of plants. ROMO estimates that it has about 423 acres (171 hectares) covered with 29 species of invasive exotic plants (National Park Service 2009).

There are three datasets that contain information on invasive species for ROMO. One is a database that contains "exotic plant locations" that has been developed by maintenance crews for weed control and management, and generally has information about exotics in the front country, along trails and roads (Figure 33).

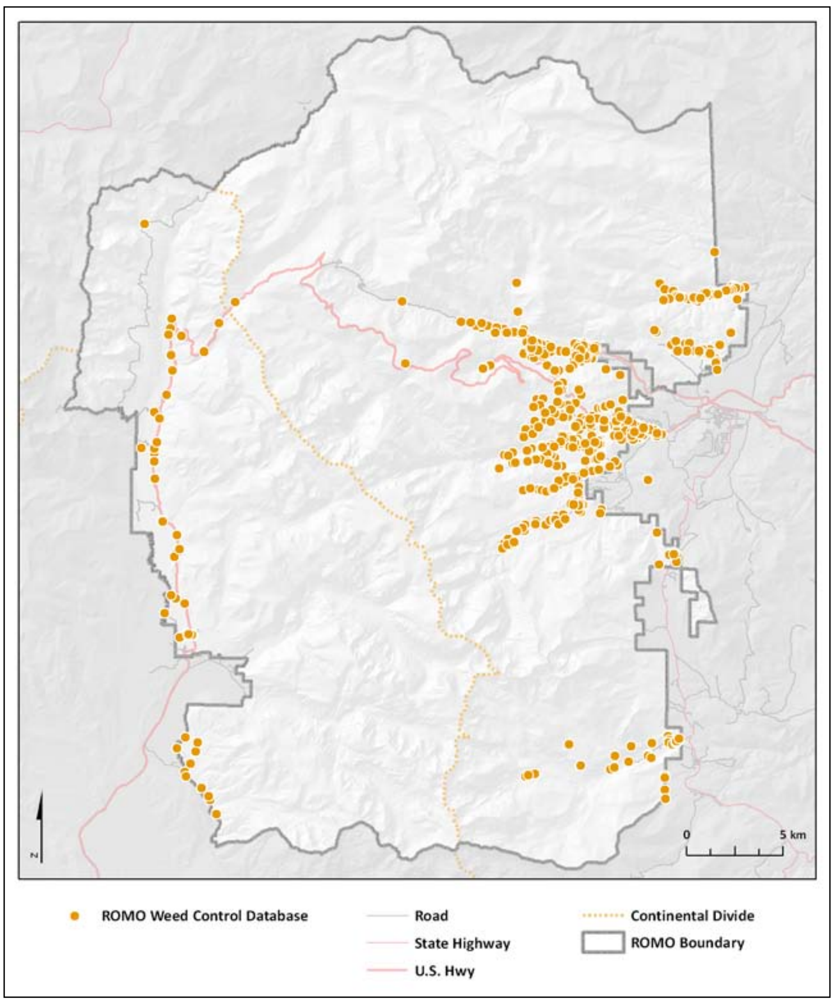


Figure 33. Distribution of known locations of exotic species from the Weed Control Database, Rocky Mountain National Park.

A second spatial dataset contains data on plant species found in the park that has been compiled by the U.S. Geological Survey through an initiative called the National Institute of Invasive Species Science (NIISS; Figure 34). This collection effort has provided the basis for a number of publications about exotic species invasions, including Chong et al. (2001) and Kalkhan et al. (2006, 2007). It also provides general patterns of exotics in the park, but because it does not cover the entire park (it is limited to a narrow east-west band through the middle of the park) and is not based on a probabilistic sample design, it does not provide a rigorous basis to establish trends or estimate populations of exotic plant species across the park.

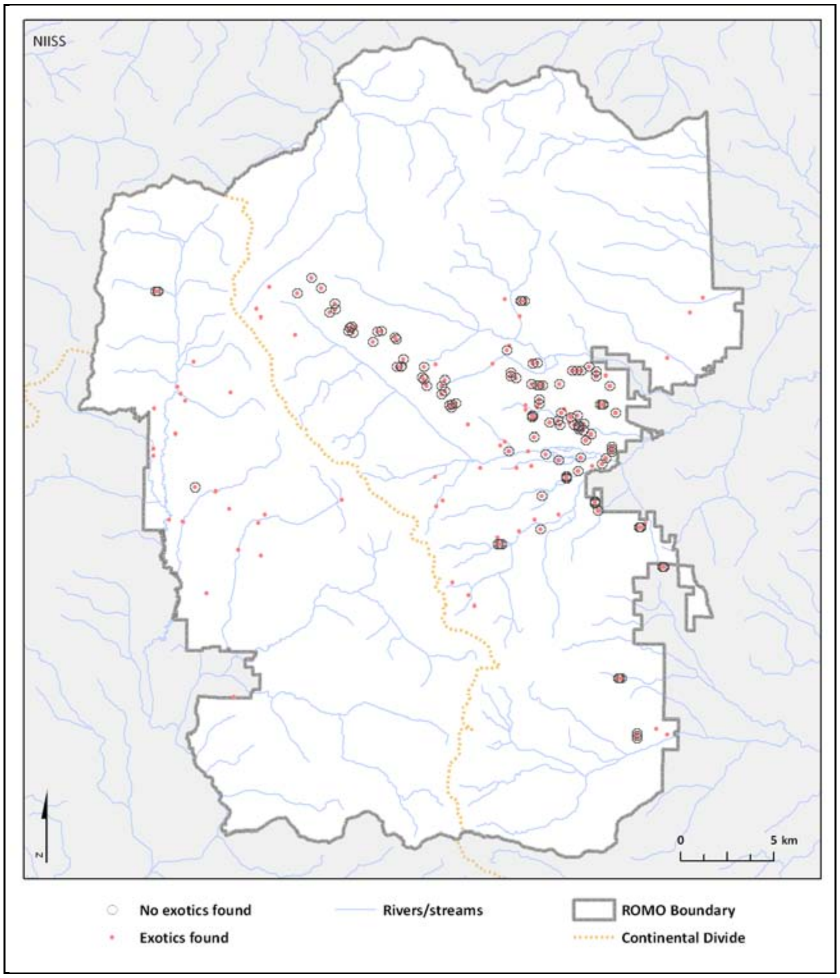


Figure 34. Distribution of known locations of exotic species from the USGS NIISS database.

However, in both of these datasets, there are large expanses of the park (particularly away from the central road corridor areas) where no data were collected. Also, because the sample design was not a probability-based, random sample design, it is difficult to develop rigorous estimates of the extent of exotic plant distribution, since the sampling effort is un-quantified. We provided a brief review of these datasets because they are commonly referred to by a variety of park and outside scientists. Also, we compared the Weed Control database to the results from the estimated extent and distribution of exotics to identify watersheds that might be under-sampled.

<u>Approach/Methods</u>
We used the 1,861 vegetation plots that were collected for the ROMO vegetation map that reflects conditions during 2001 (Salas et al. 2005). These locations were based on a GRADSECT

(Gradient-directed transects; Gillison and Brewer 1985) sampling design that targeted natural vegetation, and the sampling details are provided in Salas et al. (2005). The plant species' scientific and common names, as well as percent cover per sampling plot (including invasive exotics) were catalogued at each plot (852 records). We then reclassified each species type into one of two classes—exotic or non-exotic—by using the list of exotic species found in ROMO (Rutledge and McLendon 1996; Table 26). We then computed an overall indicator of the proportion (or extent) of exotic terrestrial plants, computed as the ratio of the cover of individuals by the total plant cover, by summarizing the percent exotic by 8, 10, and 12-digit HUCs. We also summarized the ROMO vegetation by the five generalized ecological system "zones" generated from simplifying the ROMO vegetation map: alpine tundra, upper montane, lower montane, savannah, and riparian ecological systems. See Technical Appendix 3 for more details.

Table 26. Known exotic plant species in Rocky Mountain National Park (Rutledge and McLendon 1996). *Denotes exotics that are known to occur in the park but were not found in the vegetation plots of ROMO vegetation. BOLDED species names are designated as invasive species as designated by the Natural Resources Conservation Service (USDA 2009).

Scientific Name	**Common Name**		***Scientific Name***	**Common Name**
Agropyroncristatum	Crested wheatgrass		*Lepidiumcampestre**	Field Cress
Agropyronintermedium	Intermediate wheatgrass		*Lepidiumdensiflorum**	Peppergrass
Agropyronrepens	Quackgrass		*Lepidiumperfoliatum**	Clasping pepperweed
Alopecurispratensis	Meadow foxtail grass		***Linariadalmatica ssp. dalmatica***	Dalmatian toadflax
Alyssum alyssoides	Yellow alyssum		***Linariavulgaris***	Butter and eggs
*Amaranthusretroflexus**	Redroot pigweed		*Loliumperenne*	Perennial ryegrass
*Ambrosia tomentosa**	Skeleton Leaf Bursage		*Lychnis alba**	White campion
Arabisglabra	Tower Mustard		***Lythrumsalicaria****	Purple loosestrife
*Asparagus officinalis**	Asparagus		*Matricariamatricaroides**	Pineapple weed
Barbareavulgaris	Bitter Wintercress		*Matricariaperforata**	Wild chamomile
Berteroaincana*	Hoary alyssum		*Medicagolupulina**	Black medic
Bromusinermis	Smooth Brome		***Melilotus alba and M. officinalis***	White sweetclover
Bromusjaponicus	Japanese brome		*Menthaspicata*	Spearmint
Bromustectorum	cheatgrass		*Onobrychisviciaefolia**	Sanfion
Camelinamicrocarpa	Smallseed false flax		***Phalarisarundinaceae***	Reed canary grass

Scientific Name	**Common Name**		*Scientific Name*	**Common Name**
*Capsella bursa-pastoris**	Common shepherd's purse		*Phleumpratense*	Timothy
Carduusnutans	Musk thistle		*Plantago major*	Broadleaf
*Carumcarvi**	Wild caraway		*Poaannua**	Annual bluegrass
Centaureadiffusa*	Tumble knapweed		*Poabulbosa**	Bulbous bluegrass
Centaureamaculosa*	Spotted knapweed		*Poacompressa*	Canada bluegrass
Cerastiumvulgatum	Mouseear chickweed		*Poapratensis*	Kentucky bluegrass
*Chenopodium album**	Lambsquarters		*Polygonumarenastrum*	Knotweed
Chenopodiumcapitum	Strawberry blite		*Polygonum convolvulus**	Black bindweed
*Chenopodiumglaucum**	Oak-leafed goosefoot		*Potentillanorvegica*	Norway cinquiefoil
Chrysanthememleucanthemem	Oxe-eye daisy		*Psathyrostachysjuncea**	Russian wildrye
Cirsiumarvense	Canada thistle		*Rheum rhubarbarum**	Rhubarb
Cirsiumvulgare*	Bull thistle		*Rumexacetosella*	Sheep sorrel
Conium maculatum	Poison hemlock		*Rumexcrispix*	Curly dock
Convolvulus arvensis*	Field bindweed		***Salsolaiberica****	Russian thistle
*Conyza Canadensis**	Horseweed		***Sisymbriumaltissimum***	Jill Hill Mustard
Cynoglossumofficinale*	Houndstongue		*Sisymbriumofficinale**	Common hedge mustard
Dactylisglomerata	Orchard grass		*Solanumtriflorum**	Cut leafed nightshade
*Descurainia Sophia**	Flixweed		***Sonchusarvensis****	Meadow sowthistle
*Erodiumcicutarium**	Redstemfilaree		*Spergulariarubra**	Red sandspurry
Erodiumcicutarium	Redstemfilaree		*Taraxacumofficinale*	Dandelion
Erysimumcheiranthoides	Treacle mustard		*Thlapsiarvense*	Field pennycress
Euphorbia esula	Leafy spurge		*Tragopogondubius*	Western salsify
*Festucaovina**	Sheep fescue		*Trifoliumhybridum*	Aliske clover
*Festucapratensis**	Meadow fescue		*Trifoliumpratense*	Red clover
Gypsophiliapaniculata	Babysbreath		*Trifoliumrepens*	White clover

Scientific Name	**Common Name**		*Scientific Name*	**Common Name**
Hieraciumaurantiacum*	Orange hawkweek		*Triticumaestivum**	Wheat
*Hypericumperforatum**	St. John's wort		***Verbascum Thapsus***	Woody mullein
*Lactucaserriola**	Prickly lettuce		*Verbena-bracteata**	Prostrate vervain
Lappulaoccidentalis var. occidentalis	Beggar's tick			

Reference Condition

To understand the reference condition of this indicator, we used an approach that makes the simple assumption that the park was absent of any exotic species in the reference condition – an ambient distribution, as defined by Stoddard et al. (2006). Here we make the assumption that, by definition, during "natural" conditions there were no exotic species. Although some of these taxa in the exotic species list were likely present, they are likely more widespread than before, taking advantage of disturbances in the park. However, to our knowledge there is no well-established estimate of the distributions and amounts of exotic taxa in the park under "natural" (pre-settlement) conditions.

Results/Discussion

Roughly 1.7% of the plots (weighted by percent cover) inside ROMO park boundaries were composed of exotic species (n=1,279), whereas outside of the park roughly 4.6% of the plots were composed of exotic species (n=571). Comparing the west and east sides of the continental divide, roughly 1.8% (n=483) and 2.8% (n=1,367) of the plots were composed of exotic plants, respectively. The lower montane and riparian ecological systems had the highest percentages of exotics – 5.2% and 4.6%, respectively (Table 27). The majority of plots with exotics occurred below 9,500' elevation, but 4.1% of plots between 9,500-10,500' had at least 1% exotics (1.7% of plots above 10,500').

Table 27. Proportion of plots comprised by exotic plants, summarized by ecological system class (sorted by elevation).

Ecosystem	Area (ha)	%ROMO	n	% Exotic	Standard Error (+/- %)
Alpine	35,883	33	438	0.04	0.015
Upper Montane	56,492	52	597	2.4	0.036
Lower Montane	4,680	5	204	5.2	0.051
Riparian	7,482	7	432	4.6	0.048
Savanna	3,070	3	179	1.5	0.028

Most of the exotics are located near the boundaries of the park, particularly in the heavily developed portion of the park on the eastern boundary with Estes Park (Figure 35 and Figure 36). However, exotics are found distributed throughout the ecological systems (though very few were found in alpine tundra).

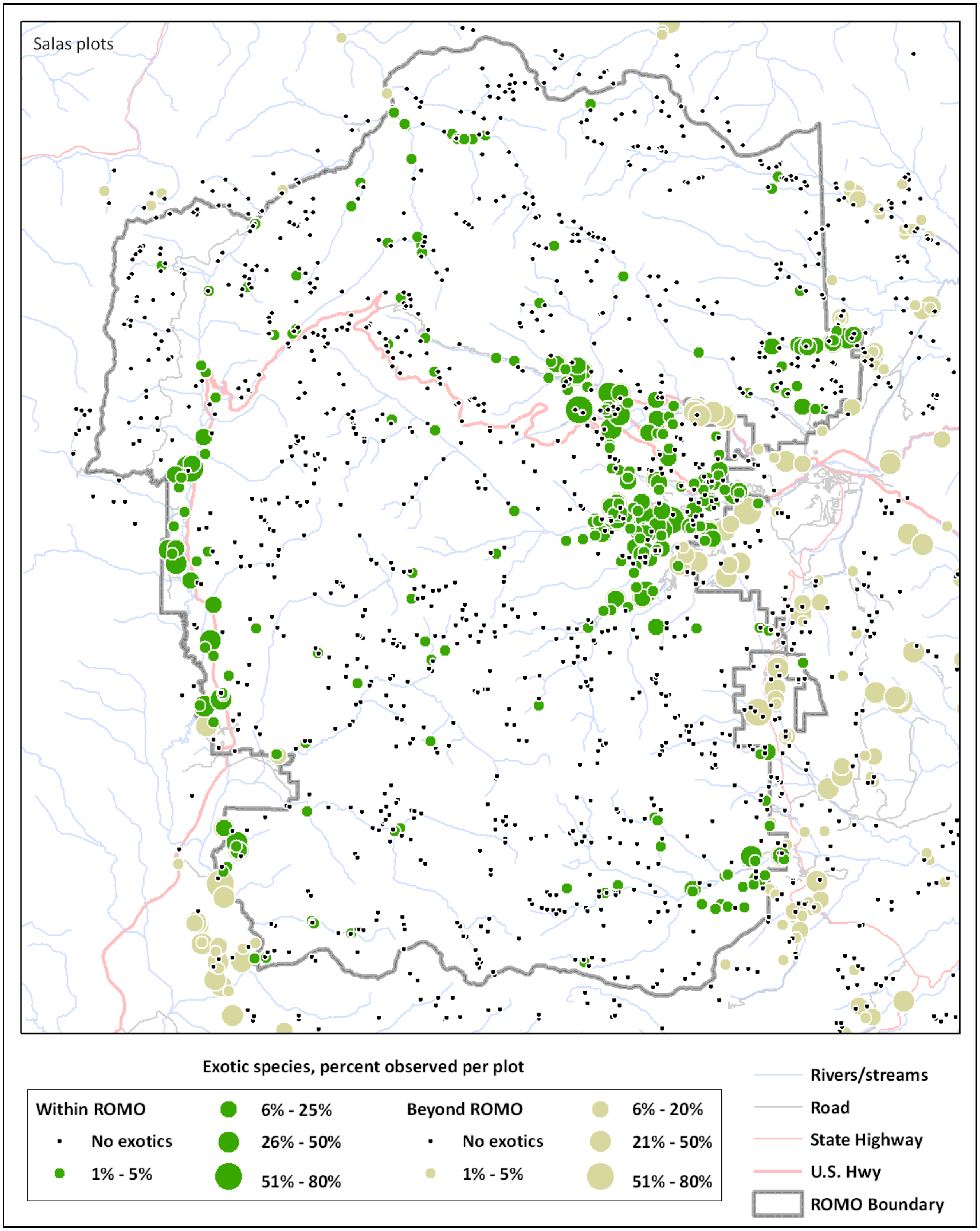


Figure 35. Percentage of exotic vegetation for each of the 1,861 vegetation plots in and near Rocky Mountain National Park (data from 2005).

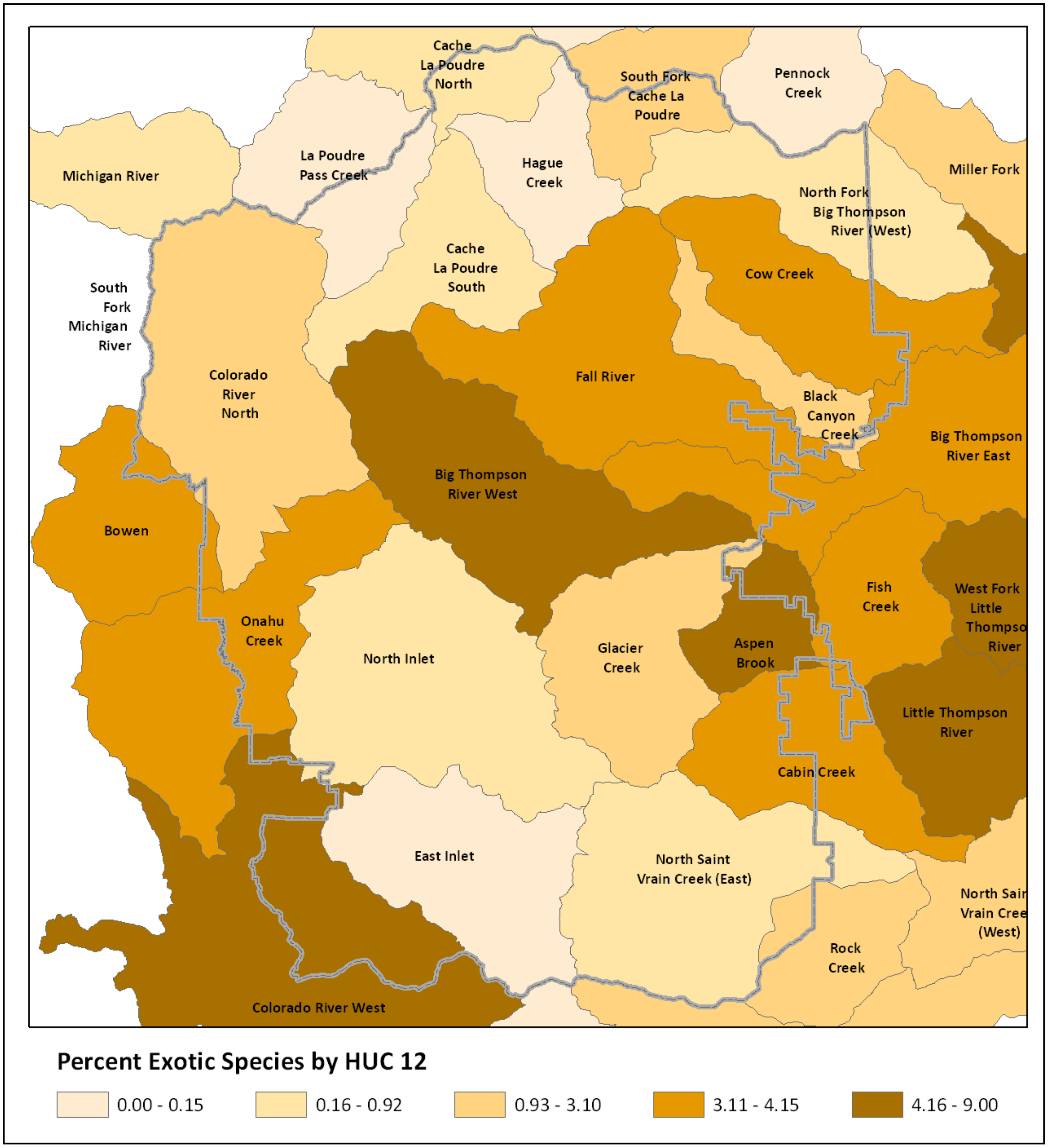


Figure 36. Percentage of exotic vegetation summarizing the 1,861 vegetation plots in and near Rocky Mountain National Park by 12-digit Hydrologic Unit Code (data from Salas 2005).

Watersheds outside of the park—and in particular on the east side near the Town of Estes Park—have higher levels of exotic plant species. Most of the front-country areas that have exotic plants are also mapped in the Weed Database, but there are a number of additional watersheds that might be important to monitor, particularly the North and East Inlet and the South Fork of the Cache la Poudre watersheds. Because of the central position within the park of the Big Thompson River West watershed, it is a priority watershed for restoration.

Pathways for exotic species

A particular management issue of concern was the relationship between visitor and exotic species patterns in the park. In particular, we examined how visitor use, accessibility, and type of use (through differentiation of trails such as horse trails and pedestrian use) are related to distributions of cheatgrass, the most abundant exotic plant species in the park. Cheatgrass is one of the most abundant exotic species in the park. We examined the relationship between where cheatgrass has been found as a function of accessibility. The strongest database to draw inference from is the ROMO Vegetation Map (Salas et al. 2004), which clearly shows that cheatgrass occurs in more accessible areas—roughly 80% of plots are within 1-hour travel time (Figure 37, Figure 38, Figure 39). The average time to plots that contain cheatgrass was 0.86 hours (SD=0.432), while the travel time to plots without cheatgrass was a mean of 3.24 hours (SD=9.1). Note that we have not conducted an analysis to infer a causal relationship. That is, relatively low-elevation, riparian areas are more accessible and so there may be some correlation with ecological systems and not accessibility per se.

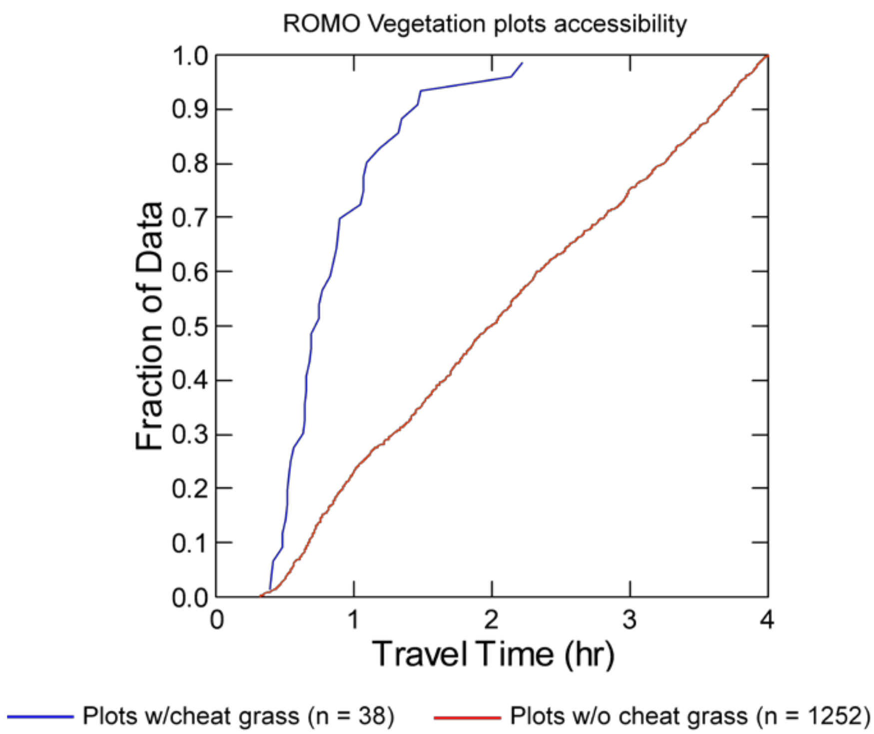


Figure 37. The relationship between cheatgrass and accessibility using the ROMO vegetation plots.

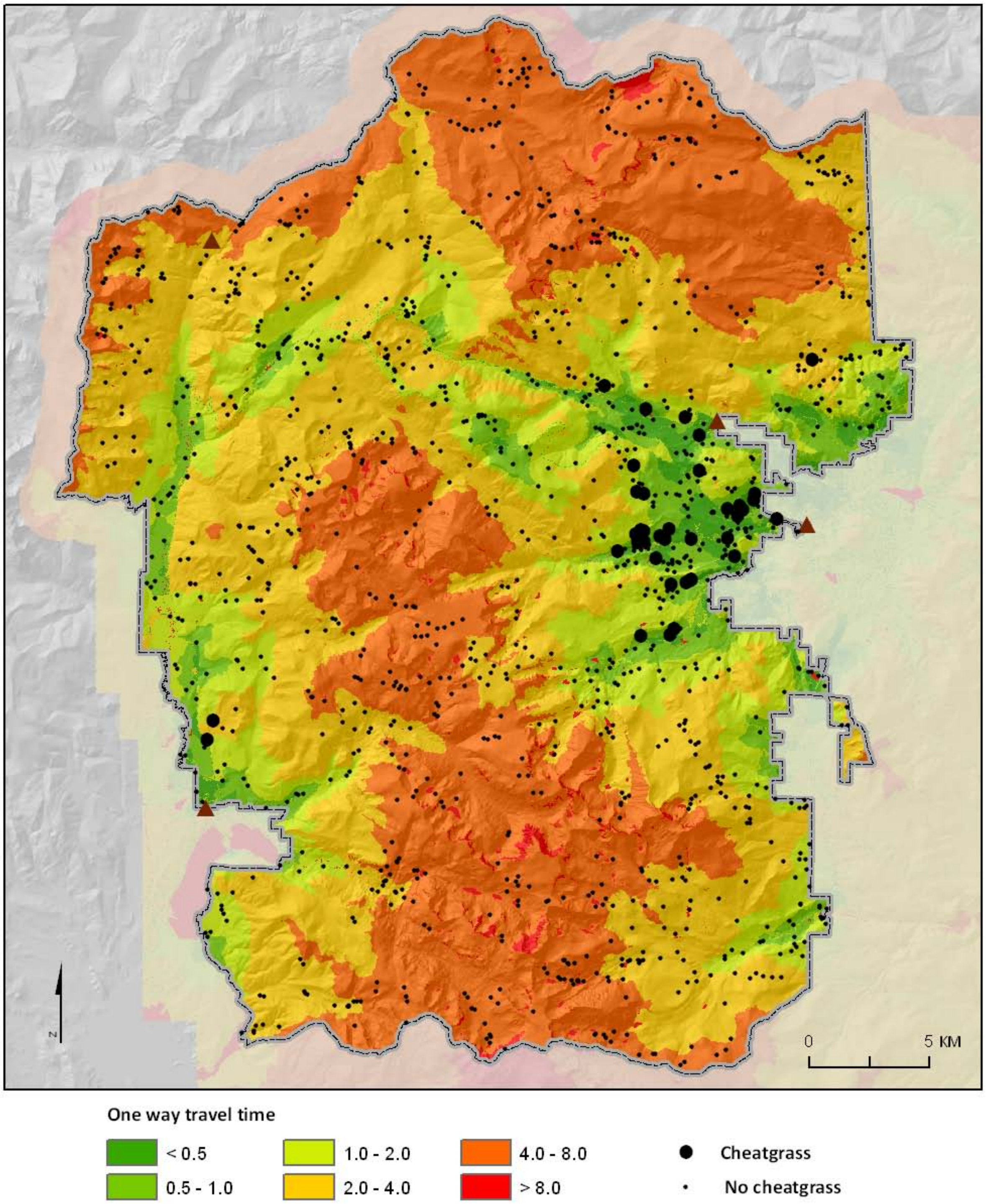


Figure 38. ROMO vegetation plots that have cheatgrass shown with accessibility map behind.

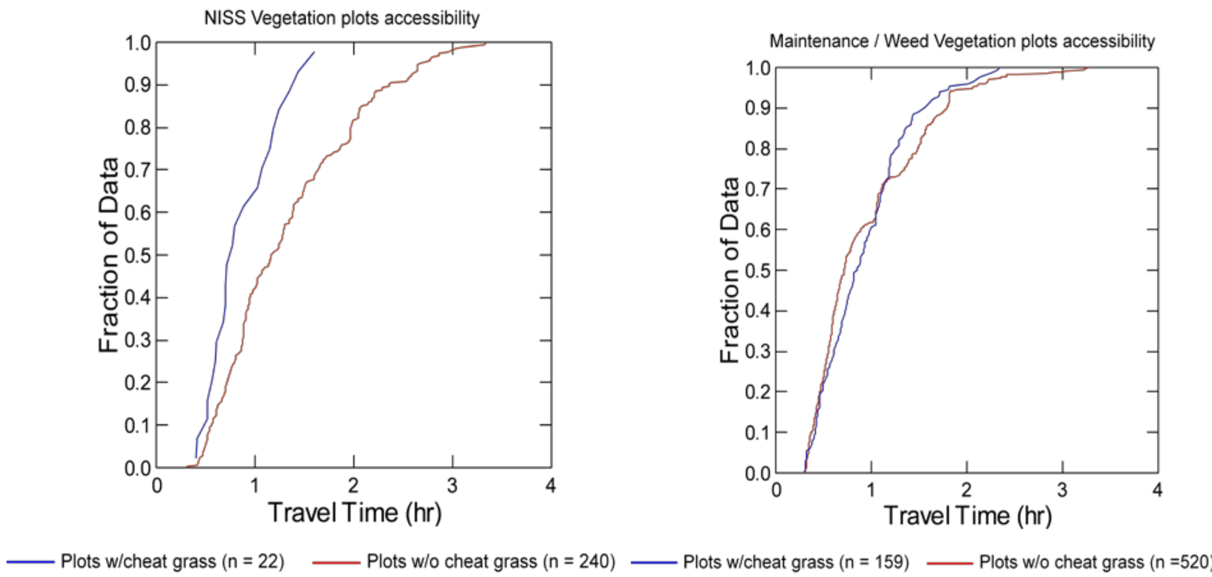


Figure 39. Data from two additional datasets provide further support that cheatgrass occurs in more accessible areas. Left: The relationship between cheatgrass and accessibility using data from NIISS. Right: accessibility compared to plot locations from the ROMO Weed Control Database.

Uses and Limitations

Overall, we believe that this indicator supports a *high degree of concern*, because of the extent and widespread disruption of the ecological processes in the park due to exotic species. We rank our level of confidence in this indicator as *moderate/moderate*. There is *moderate agreement* about the damaging effects of exotic species. There is a *moderate degree of evidence*—the ROMO vegetation plots provide a reasonable set of data on which to draw rigorous conclusions, though complementing this dataset with trend data is needed.

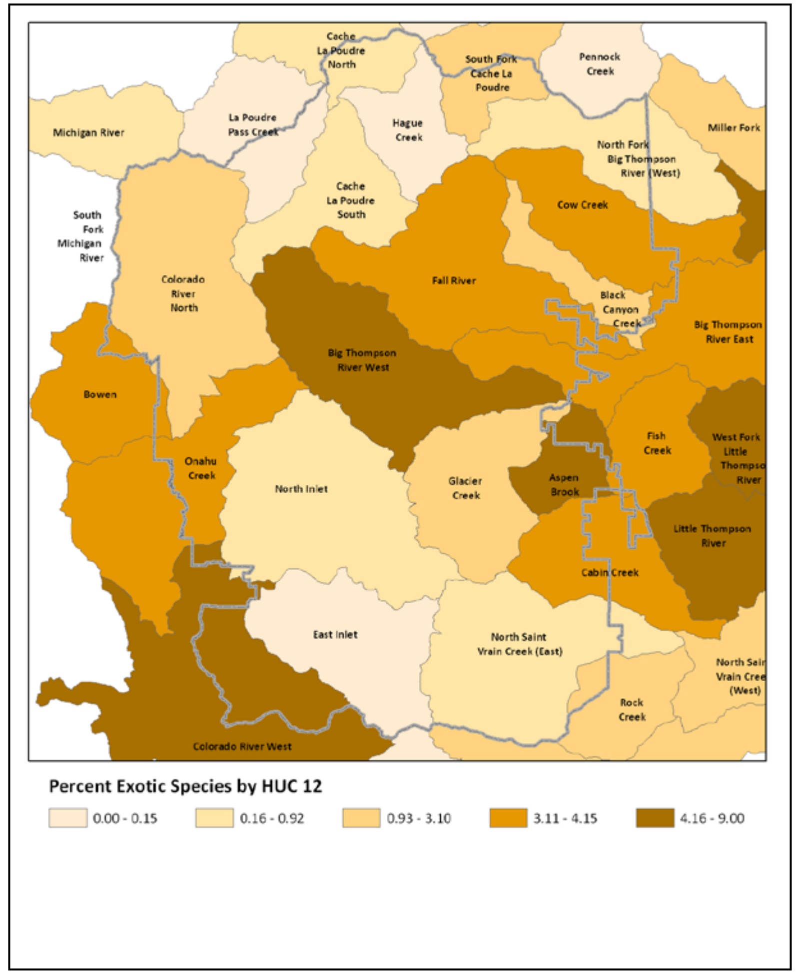
Summary: Biotic Integrity – Extent of Exotic Terrestrial Plants

What: Measures the proportion and abundance of non-native, exotic plant species weighted by percent cover in each plot of the ROMO vegetation database (Salas et al. 2005).

Why: Exotic species can displace native species, impact wildlife habitat by reducing forage and altering natural processes such as fire.

Stressors: Visitor use, land use change, climate change

Confidence: High degree of concern; moderate evidence, moderate agreement



The distribution of known locations of exotic plants (especially cheatgrass) is strongly correlated with elevation (most less than 9,500') accessibility, with roughly 80% of known locations in highly accessible areas (<1 hour). East-side watersheds have higher rates of invasive species (2.8% vs. 1.8%), and lower montane and riparian ecological systems are particularly affected.

Measure	Current condition
Proportion of exotic species*	1.7% ROMO 4.6% outside ROMO
Proportion by ecological system*	
Alpine	0.1% (0.015 SE)
Upper montane	2.4% (0.036 SE)
Lower montane	5.2% (0.051 SE)
Riparian	4.6% (0.048 SE)
Savannah	1.5% (0.028 SE)

*Total of 1,861 plots: 1,279 within ROMO boundary, 571 outside of park.

4.2.4 Biotic Integrity: Extent and Connectivity of Fish Distributions

Authors: David M. Theobald and John B. Norman, III

Description/Purpose

This indicator provides information about the extent and proportion of streams in ROMO that have non-native versus native fish. Barriers can isolate populations, potentially leading to local extinction (Gilpin and Soule 1986; Hildebrand and Kershner 2000), yet barriers can also isolate native populations from real or potential threats from non-native invaders. These potential trade-offs are particularly acute in western river systems with salmonid species (Fausch et al. 2009).

There are seven native and four exotic fish species that inhabit the aquatic system of Rocky Mountain National Park. Due to cold water temperatures and barriers to fish migration, it is probable that many of the waters within the park were originally fishless. As with most waters within Colorado, the stocking of native and non-native fish species to establish and maintain harvestable populations of trout probably started in the late 1800s and continued until the 1970s.

The objective of this analysis was to provide information about where native fish are isolated from non-native fish and where they co-exist based on three barrier scenarios: "natural", historic, and current. (These scenarios are the same as those described in the wetland/riparian area connectivity indicator section above—section 3.2.) In ROMO, the original distribution of fish was not documented until 1923, but stocking of native and non-native trout likely occurred in the late 1800s and continued until 1968. Note that at least 63 lakes were stocked with Eastern brook (n=3,492,582), Rainbow (n=750,267) and Colorado cutthroat (n=10,864) trout from ~1920-1962 (Figure 40). This provides a broad context to understand the current distribution of species, both exotic and native.

Approach/Methods

This analysis relies on the Functional Linkages of Watersheds (FLoWS; Theobald et al. 2006) tools to represent the hydrologic network that native and non-native fish travel up and down, including the restrictions to their movements based on documented barriers to movement (e.g., waterfalls). This analysis uses data from the USGS National Hydrography Dataset (1:24K) to represent streams and lakes. These relationships assume that movement throughout the stream network is unrestricted. To better inform the FLoWS with movement restrictions in ROMO, a stream barriers dataset (that was also used for the wetland/riparian area connectivity indicator) was used to alter relationships so that fish can move downstream through a barrier but not upstream (Figure 41).

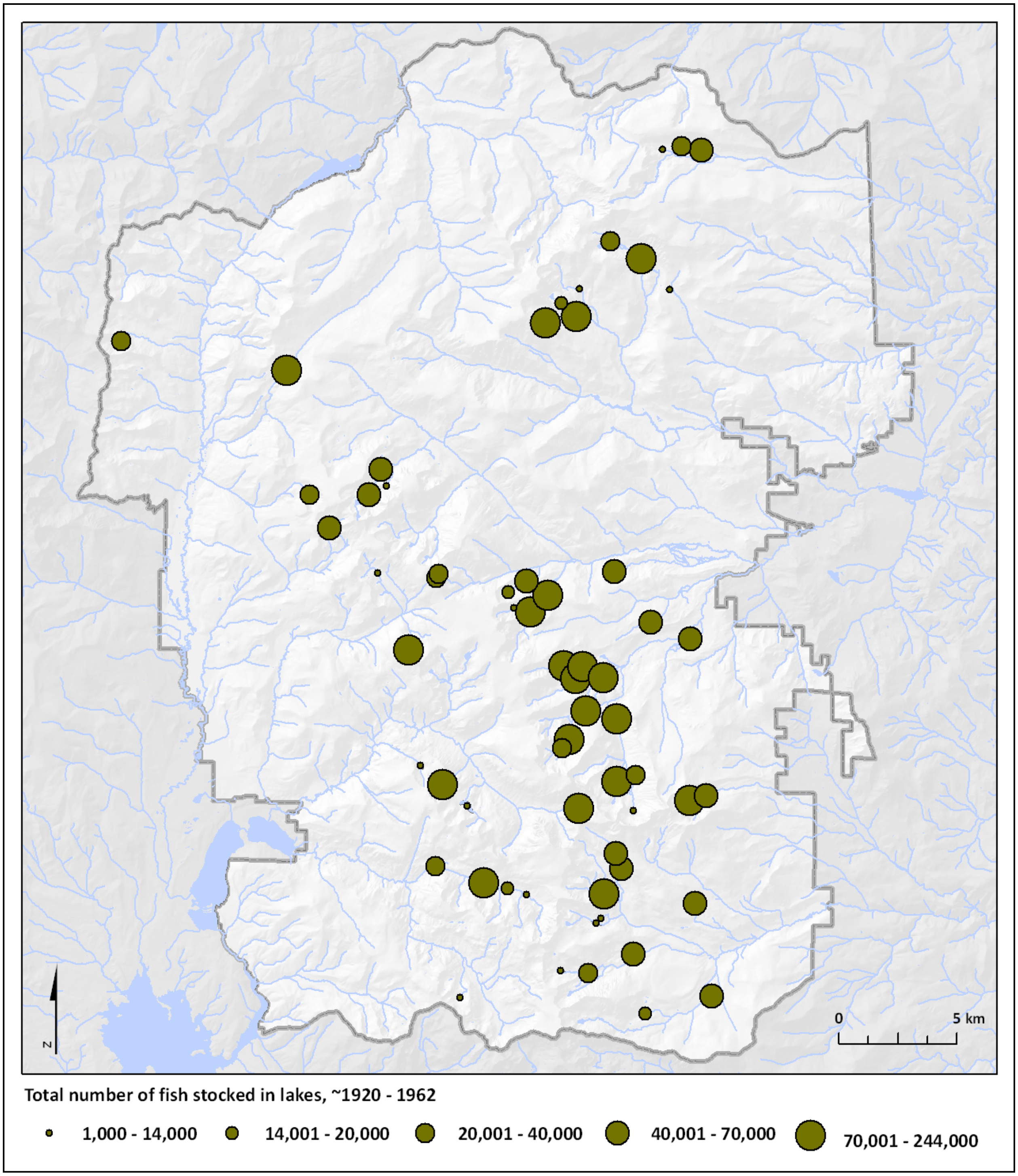


Figure 40. Total number of fish stocked in ROMO lakes from ~1920-1962.

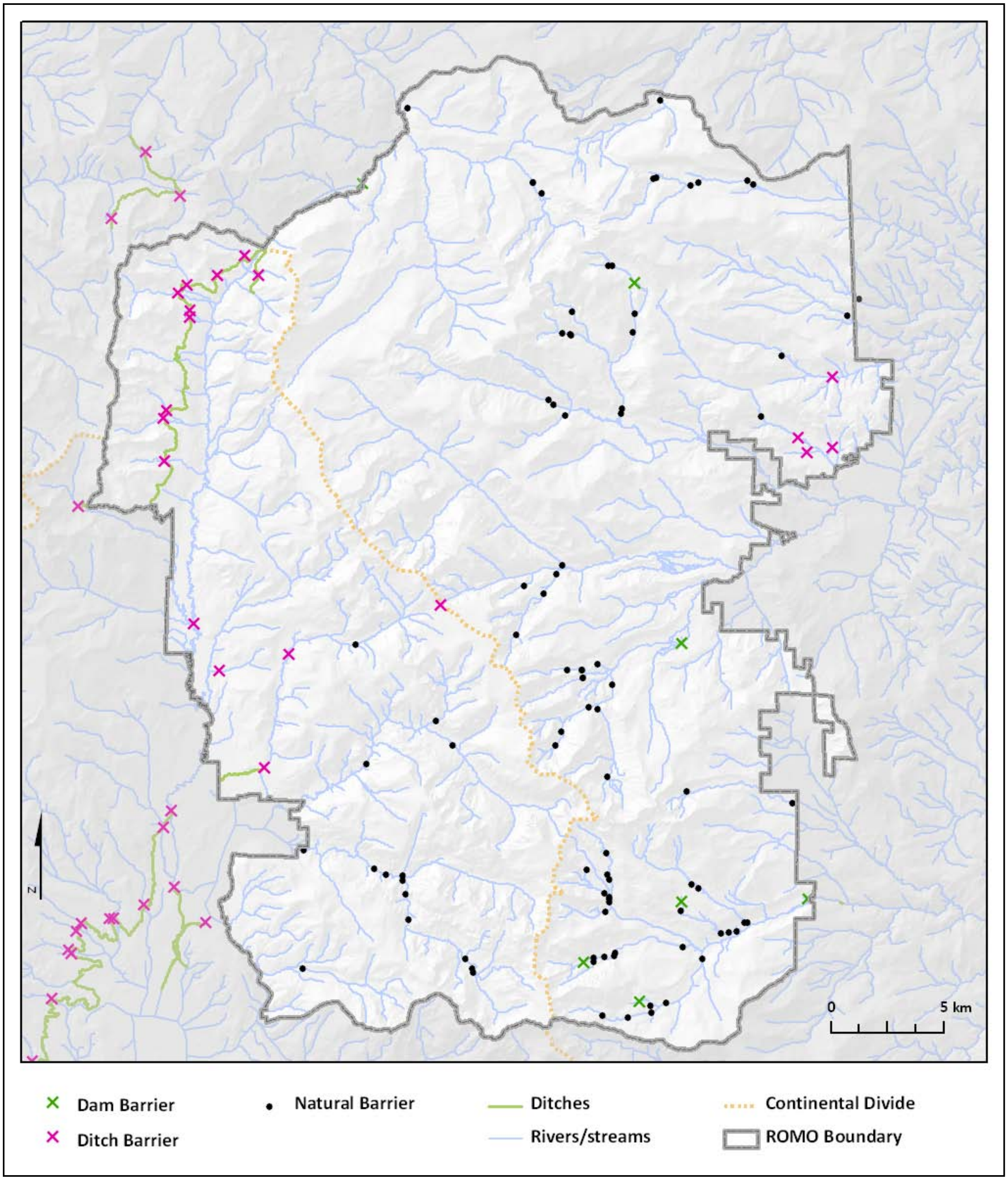


Figure 41. The known hydrologic barriers that were in the park as of 1987. There are 94 natural and 47 human barriers known within ROMO (mapped on 1:24K stream reaches, sampled and compiled by U.S. Fish & Wildlife Service, Chris Kennedy; updated March 2010). A number of ditches and dams (e.g., Sandbeach, Bluebird, and Pear lakes) were removed in the 1990s.

We used a dataset from ROMO that combined records of observed fish species in lakes and streams in and around the park that had been compiled over 20 years (U.S. Fish & Wildlife Service, Chris Kennedy).We grouped the trout species identified in the fish sample dataset into native and non-native categories. Native species include: Colorado River cutthroat and green back cutthroat trout; non-native species include: Brook trout, brown trout, cutthroat trout, rainbow trout, and Yellowstone cutthroat trout.

Figure 42 provides a map of known locations where these electro-fishing surveys were conducted (or not). We placed the native and non-native fish observations on the hydrologic network (joined to the FLoWS stream reaches) using the fish observation datasets supplied by ROMO, so that the individual stream reach in which the observation occurred was attributed. This resulted in a static spatial representation of native and non-native fish distributions within ROMO, however, does not account for possible movement of fish between stream reaches where the observations were made, nor for any potential overlap. To account for the movement of fish, we used the native and non-native designations at stream locations and then routed them up and down stream via the FLoWS network and barriers dataset (Table 28). We also defined stream reaches that were "secure" as those sections of reaches that had either "native only" or were fishless above a known barrier.

Table 28. Features that affect connectivity of fish scenarios.

Natural	**1900-1990s**	**Current**	**Feature**	**Barrier**
X	X	X	National Hydrography Dataset 1:24K flow lines	No restrictions
X	X	X	Naturally occurring lakes	No restrictions
X	X	X	Natural barriers	Up stream
	X	X	Ditch/diversion barriers	Down / Up stream
	X	X	Dams	Down / Up stream
	X	X	Other human modified features	Down / Up stream

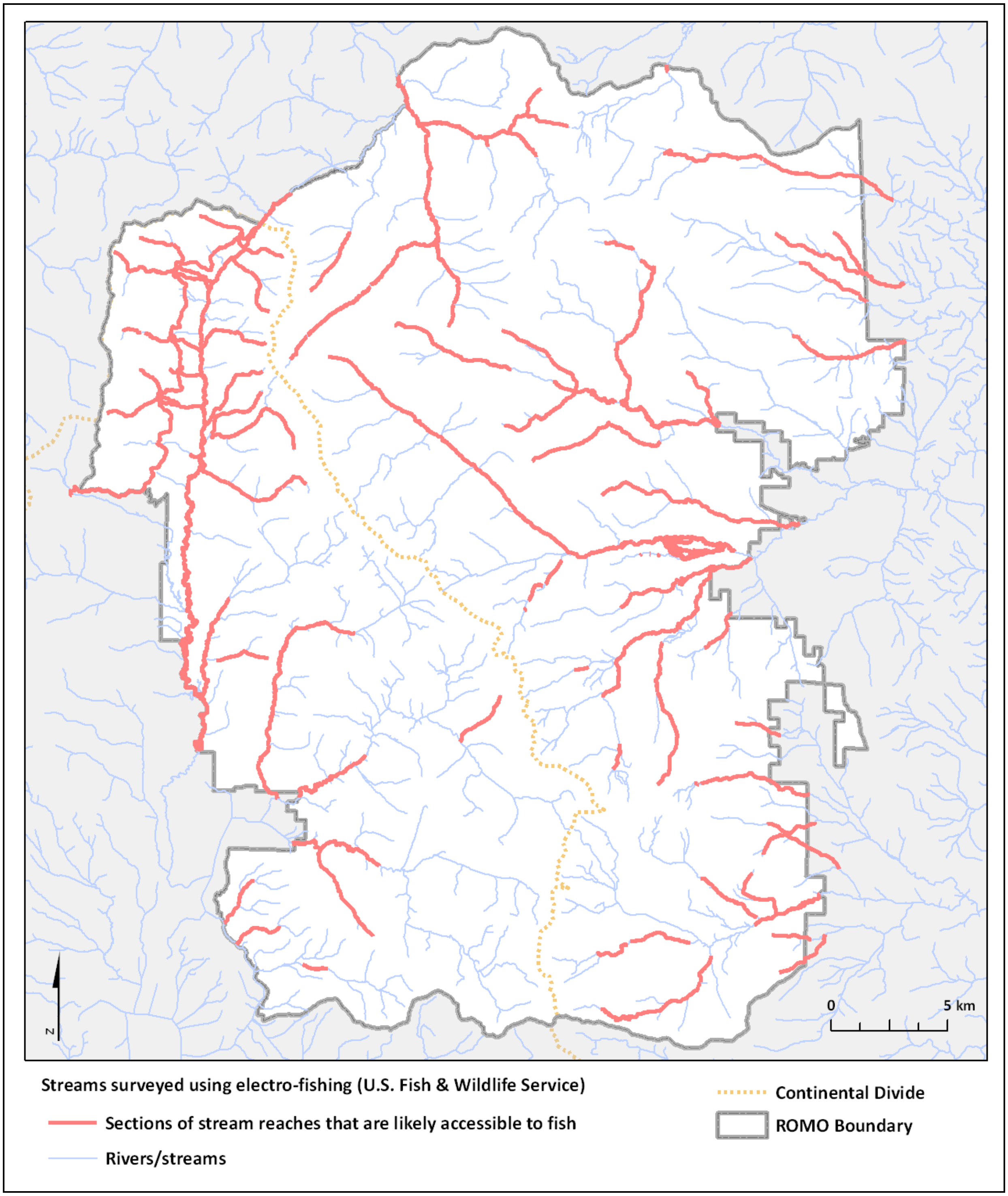


Figure 42. Sections of stream reaches that are likely accessible to fish (i.e. no barrier present between the reach location and the fish sampling location) and that have been surveyed using electro-fishing by U.S. Fish & Wildlife Service personnel (by U.S. Fish & Wildlife Service, Chris Kennedy).

Reference Condition

The reference condition we used to examine this indicator was to interpret the historical conditions using datasets recorded at earlier times (*Interpreting Historical Condition*; Stoddard et al. 2006).

Results/Discussion

We examined three scenarios to examine how barriers altered the distribution of native and non-native fish: pre-establishment of ROMO or “natural” (Figure 43); 1900s-1990s or “historic” (Figure 44), and current (Figure 45). We found that fish are present in the majority of streams (~ 90% or 923 km) for all three scenarios (Table 29). These stream reaches where fish are present also account for about 85% of hydrologically connected wetlands in ROMO. The “secure” zones (above known barriers) are highly fragmented and located high in watersheds (stream orders 1 and 2) with stream reaches where only native fish occur. These secure zones account for 77% of the native-only stream kilometers (currently) and 94% of hydrologically connected wetlands across all scenarios. The native streams experienced the smallest amount of change for the three scenarios with no change between the natural and current scenarios and minimal change for the mid-century scenario (~ 2% difference). The fishless streams exhibited the largest amount of change between scenarios with on average 24% difference from the natural scenario, but this is expected since is occupies the smallest component of the network and is restricted to first order streams.

By mid-century the creation of additional (human) barriers fragmented the “natural” hydrologic network, resulting in an expansion of streams available for non-native and fishless reaches, and a contraction of available native stream reaches (Table 29). Although there have been a few barriers removed from mid-century to current (e.g., Eureka Ditch), the current scenario shows little change in fish distributions from the mid-century scenario due to the location of removed barriers. Comparing the current configuration to the “natural” scenario (no human-modified barriers), currently there are more stream kilometers that do not contain native fish or do not contain any fish currently.

Table 29. Total stream length for scenarios and fish distributions.

	Total Stream Length (km)		
	Natural	**Historic**	**Current**
Native	74.5	72.1	75.5
Non-native	183.4	230.1	215.1
Both native and non-native	794.3	738.3	756.7
Fishless	22.1	33.8	27.8

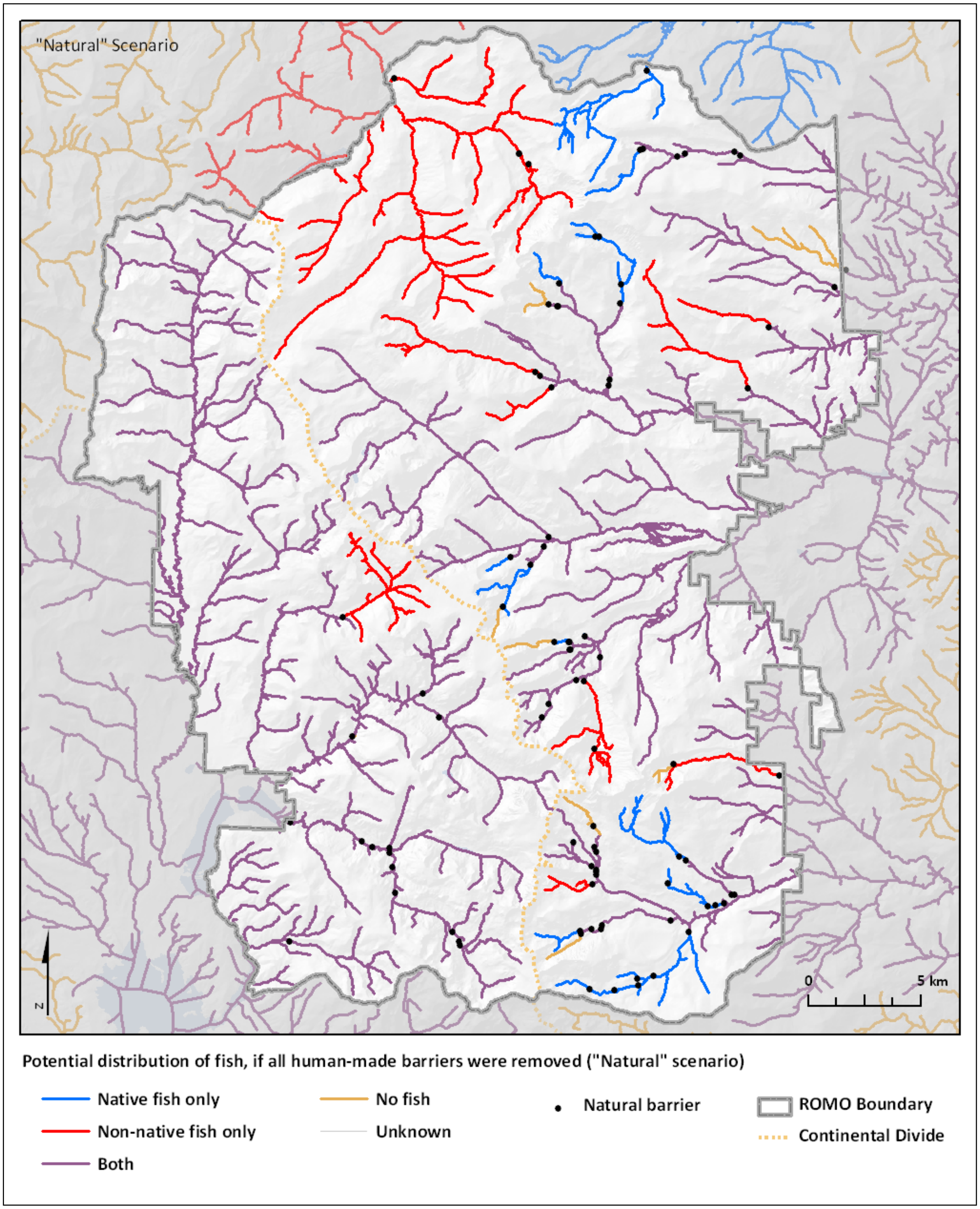


Figure 43. Distribution of native and non-native fish based on the "natural" scenario. There are non-native fish reaches in this map because the "natural" scenario reflects the removal of human-modified barriers, not removal of non-native fish. That is, given current native and non-native fish distributions, this scenario reflects how naturally occurring barriers fragment fish habitat.

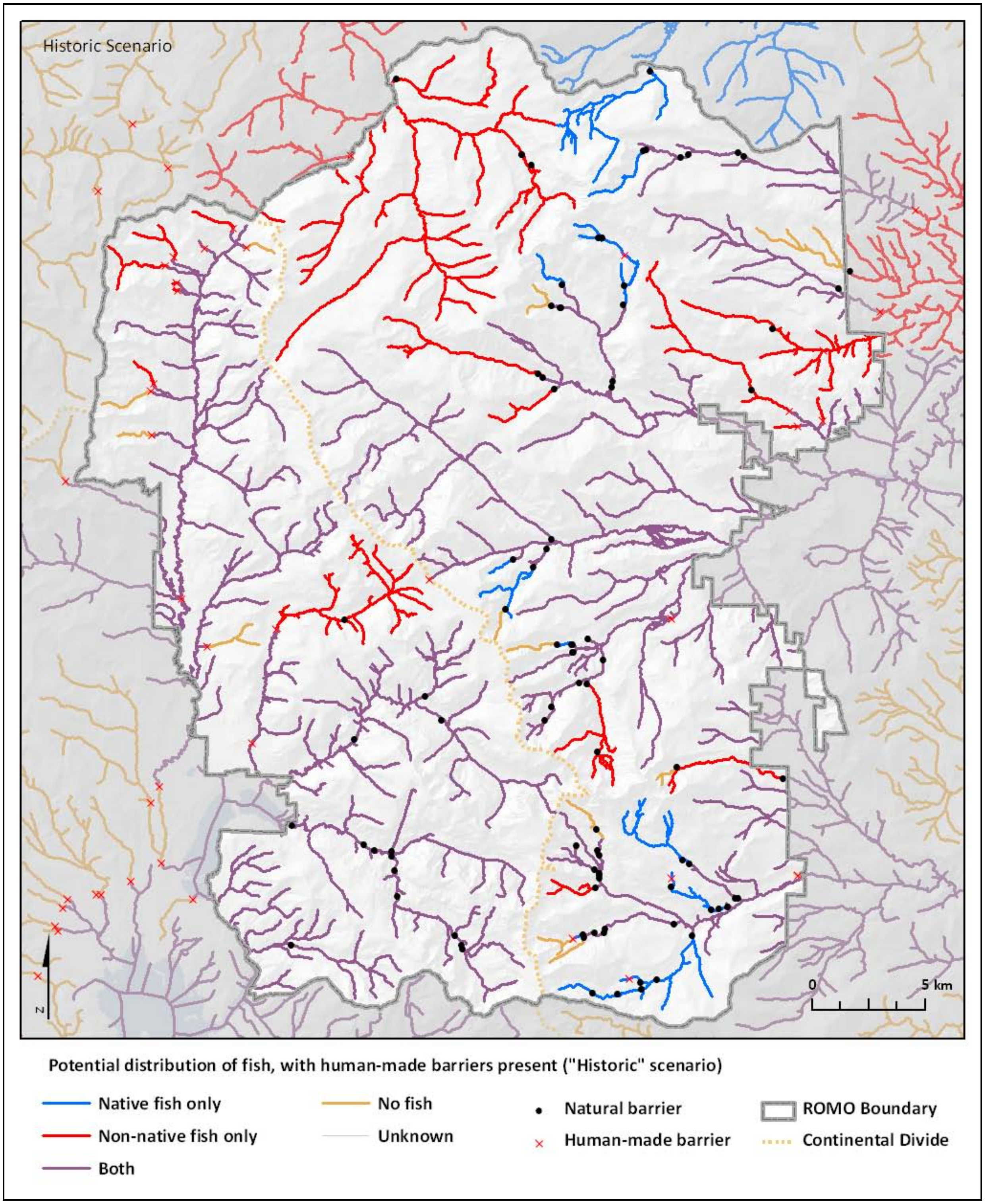


Figure 44. Distribution of native and non-native fish habitat based on the historic (1900-1990s) scenario.

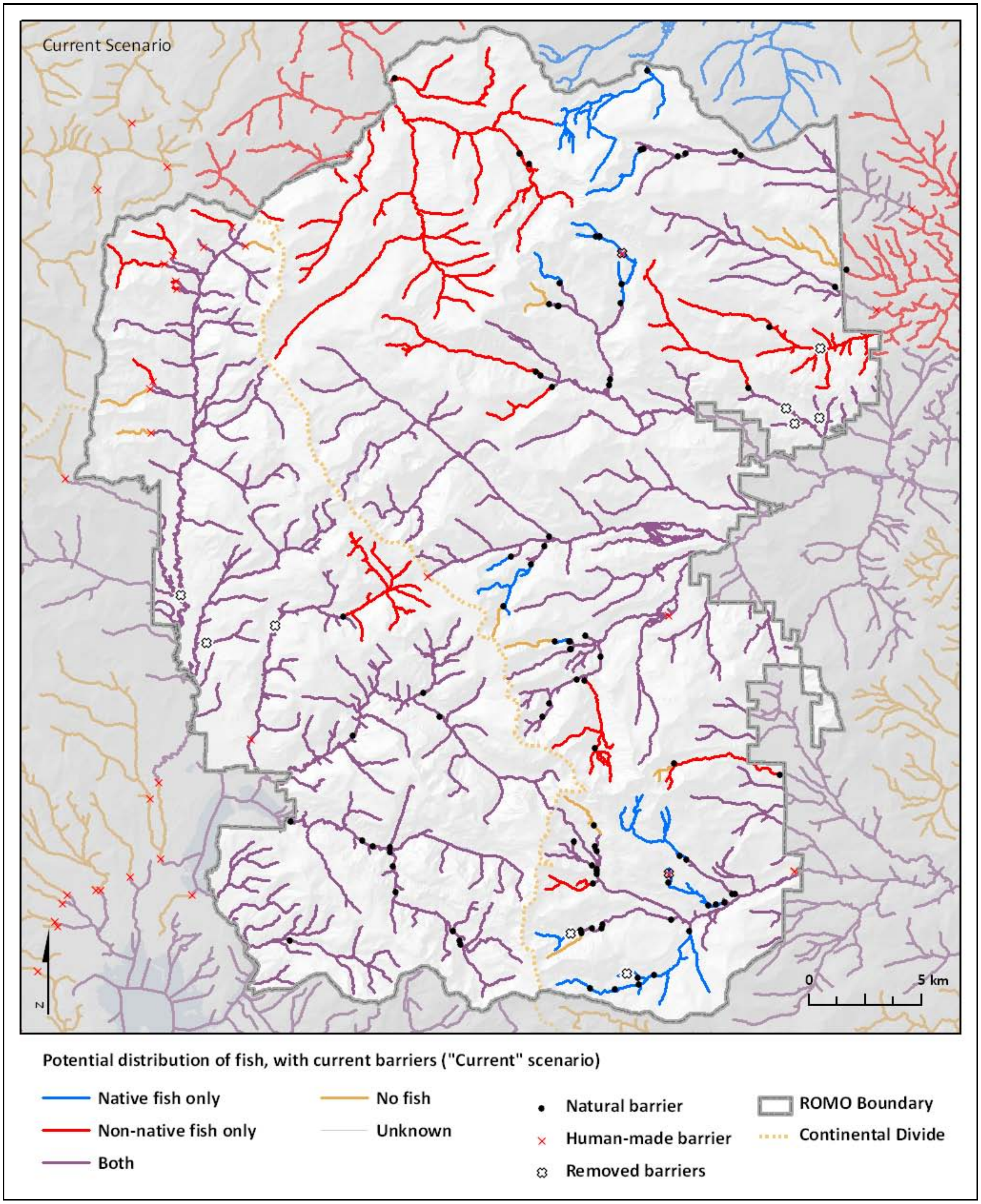


Figure 45. Distribution of native and non-native fish habitat based on the current scenario, as of current conditions in 2010. There are slight differences between this scenario and the mid-century scenario (e.g., non-fish reach in the Kawuneeche Valley). However, these scenarios are similar because the human-caused barriers that have been removed in the current scenario are located on minor streams or streams high in the watershed.

Figure 46 summarizes, by HUC12, the percent of the different fish populations by length of stream.

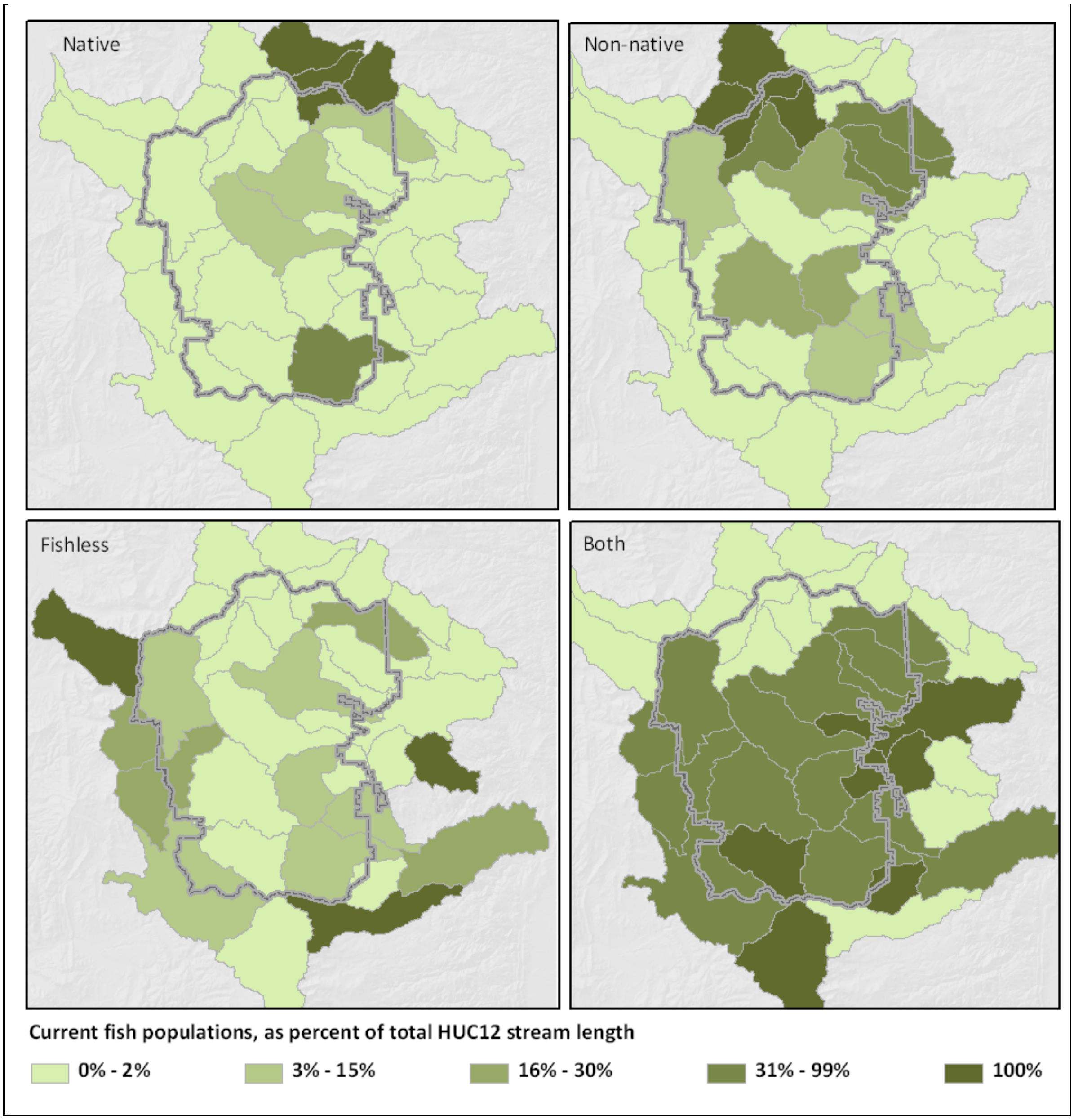


Figure 46. Summary of current native fish distribution, in total km of stream per HUC12.

<u>Uses and Limitations</u>
Overall, we believe that this indicator supports a *high degree of concern*, because of the importance of the fish to the park and the extent and widespread disruption of the hydrologic processes in the park. We rank our level of confidence in this indicator as *moderate/low*. There is a *moderate level of agreement* from experts that having refugia for native fish species is important to the long-term viability of endangered trout species. There is a *low level of evidence* about the distribution data, particularly because the distribution is based on an ad hoc sample design and there is uncertainty around the genetics of the Greenback cutthroat trout populations.

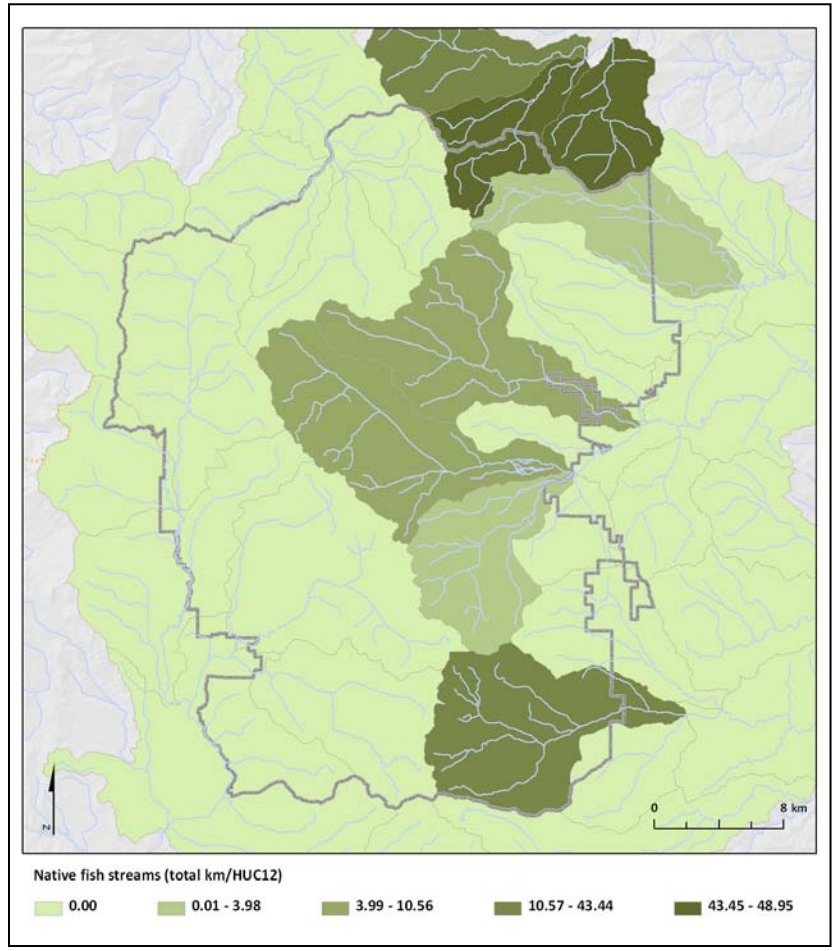
Summary: Biotic Integrity – Extent and Connectivity of Fish Distributions

What:	Measures the distribution of native and non-native fish, by incorporating observation data at streams and lakes with hydrologic connectivity (and barriers to up-stream movement).
Why:	Non-native species displace native species.
Stressors:	Riparian vegetation, visitor use, climate change
Confidence:	High degree of concern; low evidence, moderate agreement.

Currently the proportion of streams that are “secure” (native only or fishless above a barrier) is 10% and there are 54 known human barriers, and native-only streams have increased slightly from 7.0% to 7.3% in the past 50 years.

Measure	Reference Condition	Current condition
Proportion of streams with native-only fish	97.3%	7.3%
Proportion of streams with native fish	100%	75.8%
Proportion of streams* in ROMO above a barrier	100%	54%
Mean length of native-only fish streams (km)	228.5	76.1

*Total length of streams in ROMO is 1,074.2 km (at 1:24K).



4.2.5 Biotic Integrity: Extent of Suitable Beaver Habitat

Authors: Richard Scherer, Ian Leinwand, Barry R. Noon, and David M. Theobald

Description/Purpose

A key indicator for ROMO is the extent of suitable beaver habitat. In North America, the beaver (*Castor canadensis*) has near iconic status as the quintessential ecosystem engineer (Baker and Hill 2003)—a species that changes the physical structure of the environment and in the process creates niches to be exploited by otherwise absent species. As a result of their dam building, canal construction, and foraging activities, beaver have profound effects on ecosystem structure and function. Their alteration of hydrological regimes, and the many subsequent effects resulting from these hydrology changes, has been well documented (Naiman et al. 1988, Baker and Hill 2003). In a nutshell, beaver-induced changes to the structure and function of the aquatic environment have many beneficial effects on plant and animal diversity (Baker and Hill 2003). The absence, or low abundance, of beaver from a landscape can serve as a powerful indicator of declines in biological diversity. Thus, the distribution of current and potentially suitable beaver habitat was a logical choice as an important indicator of biological integrity of ROMO. Though beaver occur in lentic and riverine (and disconnected wetlands) systems, the focus of our modeling work for ROMO was on streams and rivers.

Within ROMO beaver abundance and distribution may be at a historic low because of declines in tall (> 3m) willow (*Salix* sp.; Peinetti et al. 2002, Baker 2003). In fact, declines in beaver and willow populations are strongly correlated in environments within ROMO that are heavily browsed by elk (*Cervuselaphus*). There is an apparent mutualism between beaver foraging on willow for food and building materials, and the establishment and survival of willow (Baker 2003). Beaver preferentially select tall, unbrowsed patches of willow and avoid short, hedge willow patches created by heavy elk browsing. The correlation between elk browsing, decline in the stature and vigor of willow, and declines in beaver populations has led Baker (2003:177) to conclude "…when beaver cut willow, and intense elk browsing suppresses growth, the interaction of beaver and elk herbivory will create a feedback mechanism that is negative for beaver and willow but positive, or negative, for elk depending on local conditions." In addition to elk, moose are increasingly significant browsers on willows.

While demographic and distribution data on beaver have been periodically collected in ROMO over the last 70 years, collection of these data was based on *ad hoc* sampling plans, thus inference to the entire park is problematic. However, these data can be used to examine trends in beaver populations in particular areas of ROMO. Data were collected in 1939-1940, 1964, 1980, 1994, and 1999-2000. Surveys conducted prior to 1999 are less spatially explicit and only provide data on beaver activity and abundance that can be attributed at the drainage scale. Surveys conducted by Mitchell et al. in 1999 and 2000 provide a more spatially explicit description of the areas surveyed as well as coordinates for active and historic beaver signs such as lodges, dams, and food caches. From the early survey descriptions and the results reported by Mitchell et al. (2000) we mapped current and historic beaver activity observed in 1999 and 2000 (Figure 47 and Figure 48).

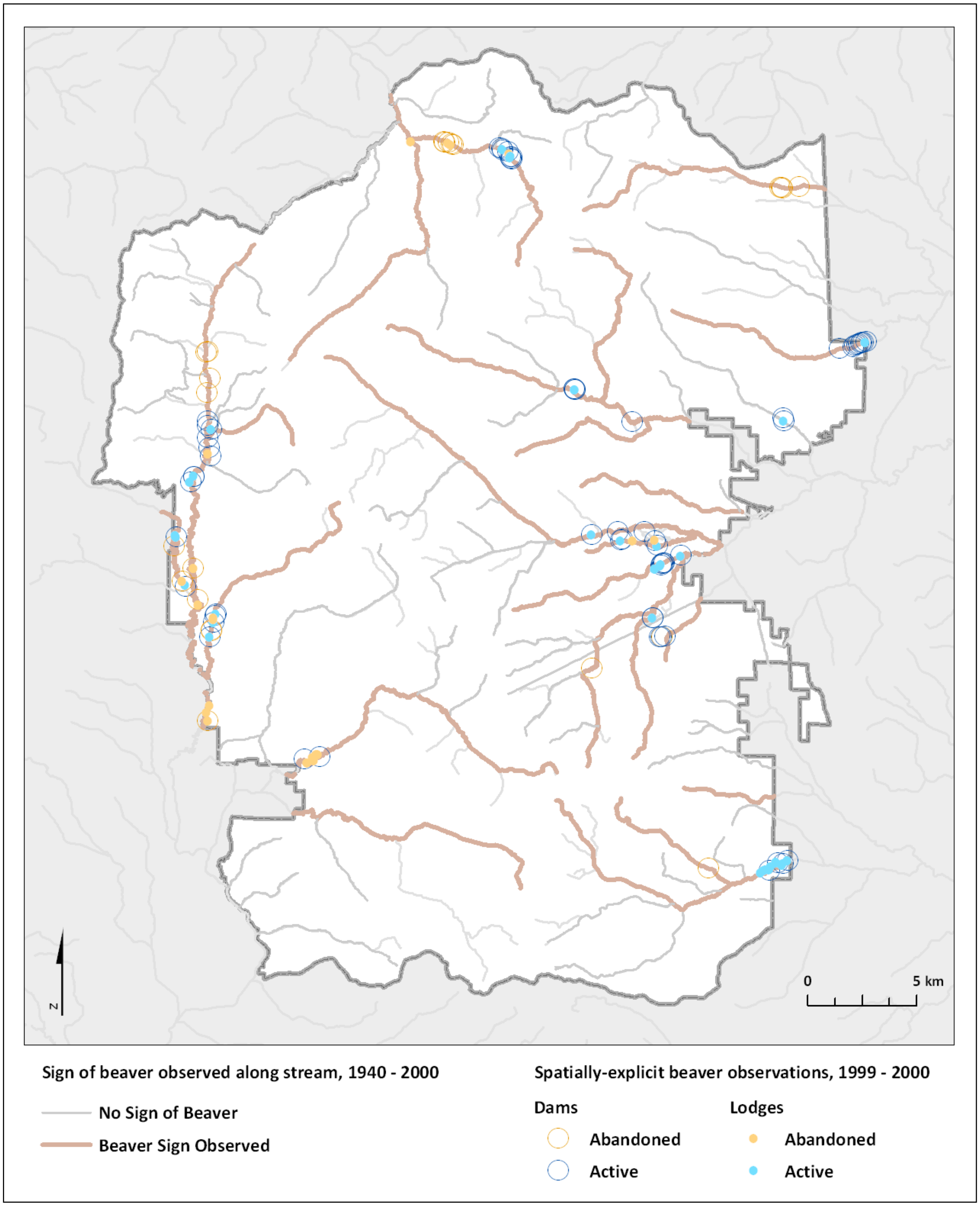


Figure 47. Historic distribution of beaver based on park survey data from 1940 to 2000. Location of lodges and dams digitized from Mitchell 1999 to 2000 data. Only portions of the drainages displayed as having signs of beaver are suitable beaver habitat. No spatial data were available for surveys conducted prior to 1999; therefore we assume that historic beaver activity mainly occurred in areas where active and abandoned dams and lodges were located. That is, we assume that dams and lodges are useful surrogates for beaver activity.

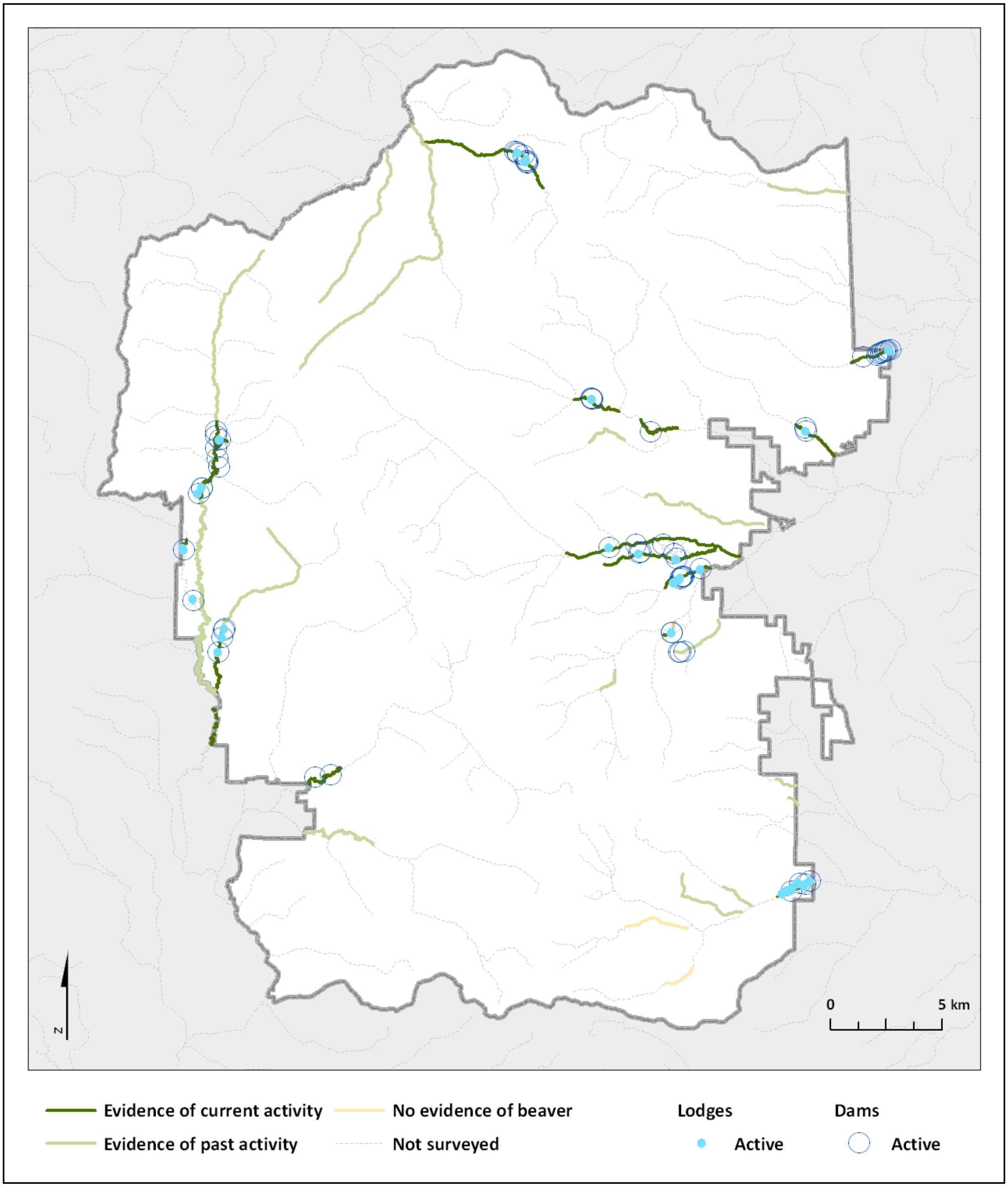


Figure 48. Areas surveyed for beaver sign in 1999 to 2000. Data digitized from ROMO beaver survey reports by Mitchell et al. (2000).

Approach/Methods

We developed a GIS of potential beaver habitat using information from the published literature and then used these data to develop a habitat suitability model. Though the published literature suggests many biotic and abiotic variables influence landscape use by beaver, spatial data were not available for many of these variables (e.g., width of stream channel; Beier and Barrett 1987, Barnes and Mallik 1997). Our final model identified potentially suitable beaver habitat in ROMO primarily using three spatial datasets: data from a digital elevation model (DEM), a stream gradient dataset and a vegetation dataset. Our map provides an estimate of the suitability of locations in the park (as pixels in the GIS data) to beaver based on the degree to which a location is accessible to beaver (defined by streams of 0-2% gradient), and the suitability of vegetation.

Below we provide an overview of the data and methods used to produce and validate the final map; see Technical Appendix 4 for more detailed methods.

We developed stream gradient using a 10 m DEM. Our model used cost distances to delineate the area around streams that was accessible to beaver. The concept of cost distance arose out of the observation that a species' behavior, perceptual abilities, and physiology will make movement relatively more costly (or less probable) across some locations or cells. For example, wood frogs (*Ranasylvatica*) are known to avoid movement through areas with dry soils and low canopy cover (Vasconcelos and Calhoun 2004). Therefore, we would expect wood frogs to avoid movement through these areas, and if they choose to move across them, we would expect the cost (in terms of physiological condition and/or survival) to be high relative to pixels that represent areas that are wetter and have high canopy cover.

Conceptually, we thought of source pixels as those pixels beaver would most likely select for dam-building. In many parts of their range, beaver create favorable aquatic conditions by damming streams (Baker and Hill 2003). We assumed pixels that represented streams where beaver would most likely build dams would serve as the centers of home ranges for individual beaver colonies. We identified the initial set of source cells by reclassifying the stream gradient dataset to select those pixels with the most suitable gradients for beaver dams. Insights into a suitable stream gradient were based on a literature review of studies from mountainous terrain in the western U.S. Of the 53 beaver dams detected by Beier and Barrett (1987) in the Truckee River Basin in California and Nevada, 48 (91%) were found at locations where the stream gradient was 0 – 2%. Of the 45 sections of stream with beaver dams sampled by Slough and Sadelier (1977) in British Columbia, 36 (80%) had gradients < 2%. Therefore, we reclassified stream pixels as source cells if their gradient was < 2%. All other stream pixels were not considered sources cells (i.e. they were reclassified as 'NoData').

We removed from consideration short (<50 m) stretches of stream as well (roughly 10%). Beaver are characterized as central-place foragers, which means they cut vegetation from one location and bring it back to a central location (e.g., dam, food cache or lodge; Baker and Hill 2003). As they exhaust the supply of suitable vegetation around a central place, they must establish a new central location. Therefore, we assumed short stretches of stream would not be able to support beaver over long periods of time, as they would not be able to move up and down the stream in response to the dwindling supply of suitable vegetation. Therefore, we eliminated all source cells that were connected to fewer than six other source cells. We suspect stretches of stream much greater than 50 m are required for beaver populations to persist over long periods of time. However, the literature did not provide clear guidance on a more appropriate length, and we chose to error toward inclusion.

We designated the resistance or cost of movement to be an integration of the willingness of the species to cross a particular landscape type, the physiological cost of movement across the landscape type, and expected reductions in survival associated with movement across the landscape type (Compton et al. 2007). We assigned costs to pixels based on the gradient of the pixel. We assumed beaver would be less willing, or find it more costly, to move through pixels with steeper slopes. For a given slope, we also assumed the cost of movement for beaver within a stream channel was much lower than the cost of movement over land. Therefore, we assigned different costs to pixels based on the slope of the pixel and whether the pixel represented a stream or terrestrial area (Table 30). Cost was assumed constant across vegetation types.

Table 30. Cost weights assigned to stream and terrestrial pixels of different gradients.

Gradient	Stream	Terrestrial
0 – 2%	Source pixels	10
> 2% – 10%	1	30
> 10% – 20%	3	50
> 20%	100	150

We then found all locations within 1,000 cost-meters of source pixels. This maximum distance assumed beavers could access terrestrial areas up to 100 m from a source pixel, if the intervening terrestrial landscape had a gradient from 0% to less than 2%. Since each pixel is approximately 9 m on a side and the relative cost of movement across pixels that represent terrestrial areas with a slope from 0% to 2% is 10 (Table 30), a beaver would use approximately 90 cost-meters to move across a single pixel. Therefore, it could travel across a maximum of 11 of these pixels or 99 m. In terrestrial areas of higher slope, the maximum geographic distance of accessible terrestrial areas was approximately 30 m. This geographic distance is consistent with the maximum movement distances for beaver away from water reported by Baker and Hill (2003).

To identify pixels that were more likely to contain vegetation and other cover types used by beaver, we used the ROMO vegetation dataset (Salas et al. 2005). Nearly all of the cover types in the map were characterized by a list of associated plant species. We used this list to identify classes that were likely to contain vegetation used by beaver. For the vegetated cover types, we considered classes characterized as having deciduous shrubs and trees of a variety of species such as willow, alder, aspen, and cottonwood (Table 31); Baker and Hill 2003, DeStefano et al. 2006). Beaver appear to prefer relatively tall (≥ 3m) shrubs (Baker 2003). However, we had limited data with which to infer shrub height from the vegetation dataset, so our map will likely overestimate the area of vegetation useful to beaver. Beavers are also known to use lakes, reservoirs and other water bodies (Baker and Hill 2003) with access to suitable vegetation. Therefore, we also considered pixels classified as streams, lakes or reservoirs as suitable for beaver. Ultimately, we identified 10 of the 46 classes as likely to contain vegetation used by beaver and 3 of the 46 classes as suitable types of water bodies (Table 31). Although herbaceous wetlands may facilitate dispersal, they were considered unsuitable habitat because they generally do not support the size of woody plants needed for dams, lodges, and forage. All other classes were considered unlikely to contain vegetation used by beaver or to represent unsuitable habitat.

Table 31. The original vegetation classes of Salas et al. (2005) and our reclassification with respect to each class's utility and suitability to beaver.

CLASS	LIKELY/SUITABLE BEAVER HABITAT
13	Shrub Upland – Alpine
15	Riparian Aspen
18	Upland Aspen
32	Cottonwood
51	Streams – Rivers
52	Natural Lakes – Ponds
53	Reservoir - Stock Tanks
120	Shrub - Riparian - Cross Zone > 9600 ft
121	Shrub - Riparian - Cross Zone < 9600 ft
161	Mixed conifer w/ aspen (Ponderosa Pine)
162	Mixed conifer w/ aspen (Lodgepole Pine)
163	Mixed conifer with aspen (Douglas-fir)
164	Mixed conifer with aspen (Spruce - Fir)

CLASS	UNLIKELY/UNSUITABLE BEAVER HABITAT
1	Herbaceous Upland – Alpine
2	Herbaceous Upland - Alpine Fellfield
4	Herbaceous Upland – Montane
5	Herbaceous Wetland – Marsh
6	Herbaceous Wetland – Wetland
7	Herbaceous Wetland - Alpine Meadow
9	Alpine - Ice Field – Glacier
10	Rock (Alpine - Upper Subalpine)
11	Rock (Foothill - Lower Subalpine)
14	Shrub Upland - Lower Montane
20	Montane Douglas Fir
22	Subalpine mixed conifer
23	Lodgepole - high elevation > 9500 ft.
24	Lodgepole - low elevation < 9500 ft.
26	Lodgepole pine – Rock
33	Juniper Woodland
34	Ponderosa Pine – Graminoid
35	Ponderosa Pine – Rockland
36	Ponderosa Pine – Shrubland
38	Limber Pine
39	Ribbon Forests
41	Disturbance – Dead and Down
43	Blue Spruce
46	Talus
47	Outwash
48	Exposed Soil - Man made
49	Cliff Face - Bare Soil
141	Shrub Upland - Big Sagebrush
142	Shrub Upland – Bitterbrush
190	Upper Montane, Mixed Conifer – Riparian
191	Upper Montane, Mixed Conifer – Riparian
400	Krummholz
999	Un-vegetated Surfaces

We assumed that pixels would have relatively high suitability scores if they contained a suitable cover type and were accessible to beaver from sections of stream with low gradient. Pixels that had suitable vegetation cover but were outside the 1,000 cost-meter boundary were not considered suitable. Pixels that had suitable vegetation cover and had a cost distance <1,000 cost-meters were considered suitable.

The preceding steps resulted in a pixel-based map of habitat suitability for beaver across the park (Figure 49). Pixels in the map are approximately 80 m^2. However, daily and seasonal movements and dispersal occur over much broader spatial scales for beaver (Wheatley et al. 1997, DeStefano et al. 2006), which suggests they would integrate information across multiple pixels in our map. Therefore, we aggregated pixels into patches of suitable beaver habitat. We delineated patches by considering a pixel part of a larger patch if it had a beaver habitat suitability score greater than 0 and was directly adjacent (i.e., shared an edge or corner [an 8-cell neighborhood]) to another pixel with a suitability score greater than 0. In some areas, our model identified lakes, ponds and reservoirs as suitable beaver habitat despite the fact that no suitable vegetation was nearby (e.g., alpine lakes). We considered these to be misclassification errors. These errors were caused by the fact that some lakes and ponds were represented as streams in the original stream gradient data set, and we included lakes, ponds, and reservoirs as useful cover types for beaver. To correct these errors, we eliminated patches when the majority of pixels in the patch were classified as lakes, ponds and reservoirs and no pixels of suitable vegetation types were nearby. We used aerial photography of the park to confirm that the deletions were appropriate. Our logic was that a pixel classified as a lake, pond or reservoir would only be used by beaver if it were adjacent to pixels with suitable vegetation.

To validate our suitable habitat map, we used data on current and past beaver presence. Mitchell et al. (2000) and Mitchell and Ducharme (*unpublished data*) conducted surveys for beaver in four drainages and nine creeks in Rocky Mountain National Park in 1999 and 2000. These reports include lists of locations of current and past beaver presence (e.g., dams, lodges, and food caches). Current locations of beaver activity were distinguished from locations of past beaver activity by the presence of fresh sign (e.g., active beaver trails, fresh cuttings, and mud; Mitchell et al. 2007). The reports yielded evidence of beaver presence at 180 locations in the park. If our final beaver habitat suitability map was useful, we would expect the locations of current beaver presence to be within pixels of high suitability.

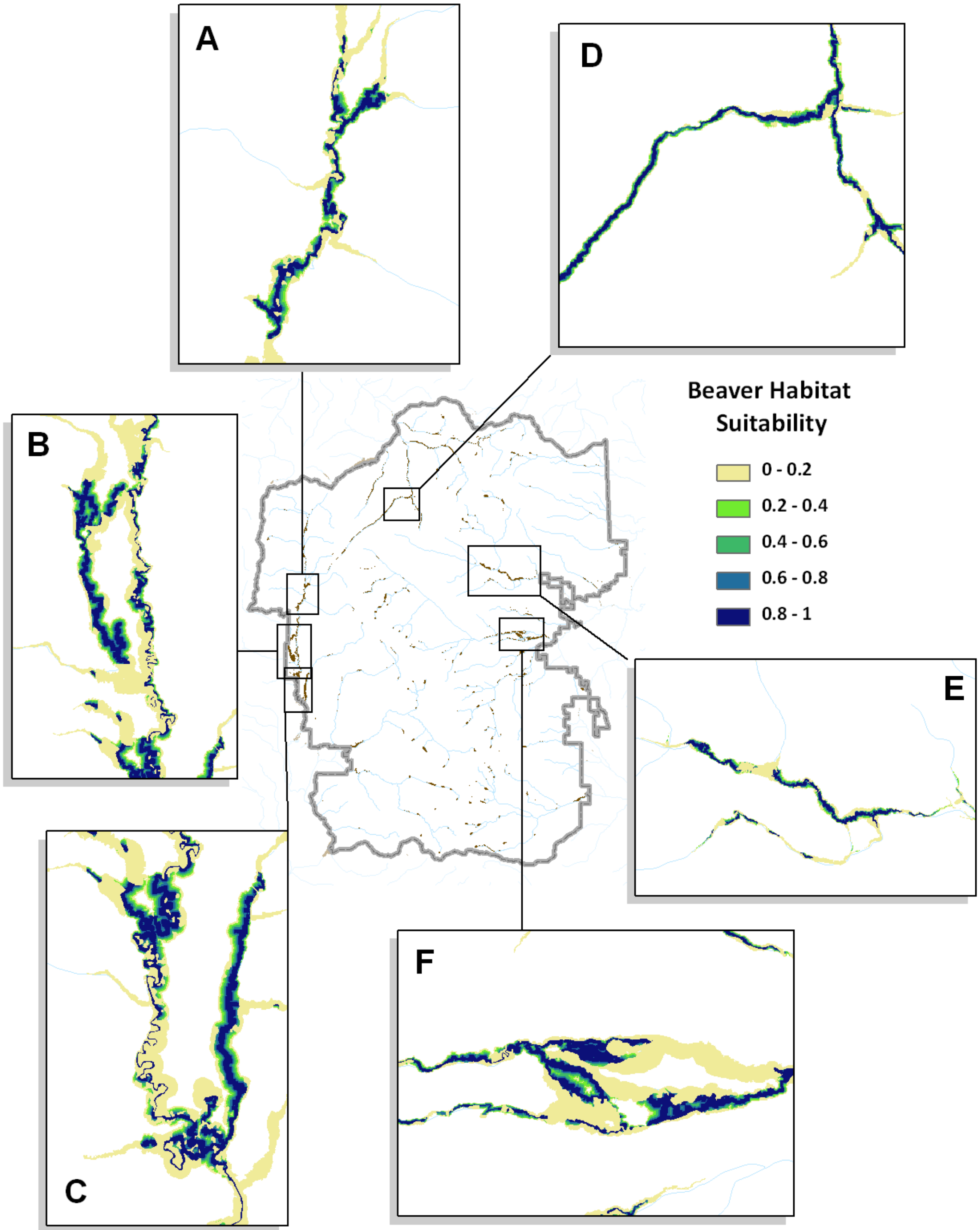


Figure 49. Areas of beaver habitat suitability in Rocky Mountain National Park. Areas in boxes represent the largest and highest scoring areas of potential beaver habitat within the park. A) The confluence of the Colorado River with Squeak Creek, Phantom Creak, Beaver Creek, and Timber Creek from north to south; B) The Colorado River and Baker Creek; C) The confluence of the Colorado River with Onahu Creek; D) The Cache la Poudre River meeting Chapin Creek; E) Fall River with Roaring River in the northwest and Hidden Valley Creek to the south; F) The Big Thompson River to the north of Cub Creek and Mill Creek.

Our final beaver habitat suitability map would not have predicted the locations of 66 of the 180 locations of current or past beaver presence (from Mitchell et al. 2007). These omission errors may be attributable to a too conservative definition of suitable habitat. Forty (22% of all the locations) were greater than 1000 cost-meters from the nearest source cell (i.e., inaccessible to beaver according to our model). However, the fact that over 80% of these locations were close to patches (within 50 m; Figure 50) suggests our map provides a reasonable representation of current and potential suitable beaver habitat in the park. It also indicates that our assumptions resulted in a fairly conservative estimate of beaver space use. Twenty-six of the 180 locations (14%) were in pixels that were accessible to beaver but not likely to be useful or suitable (beaver habitat suitability score = 0). These may be a consequence of inadequacies in the map or any of a variety of mapping errors (e.g., errors in the vegetation data set, errors in the locations of beaver presence, or projection errors). The majority of locations of beaver presence (114 of 180 locations or 63%), however, were in pixels with suitability values that ranged from greater than 0 to 1, even though pixels with these suitability values were rare according to our map (< 3% of the pixels). Seventy-eight locations of beaver presence (43%) were in pixels with high suitability values (suitability values > 0.8), but only 0.2% of the pixels in our model had the suitability values >0.8.

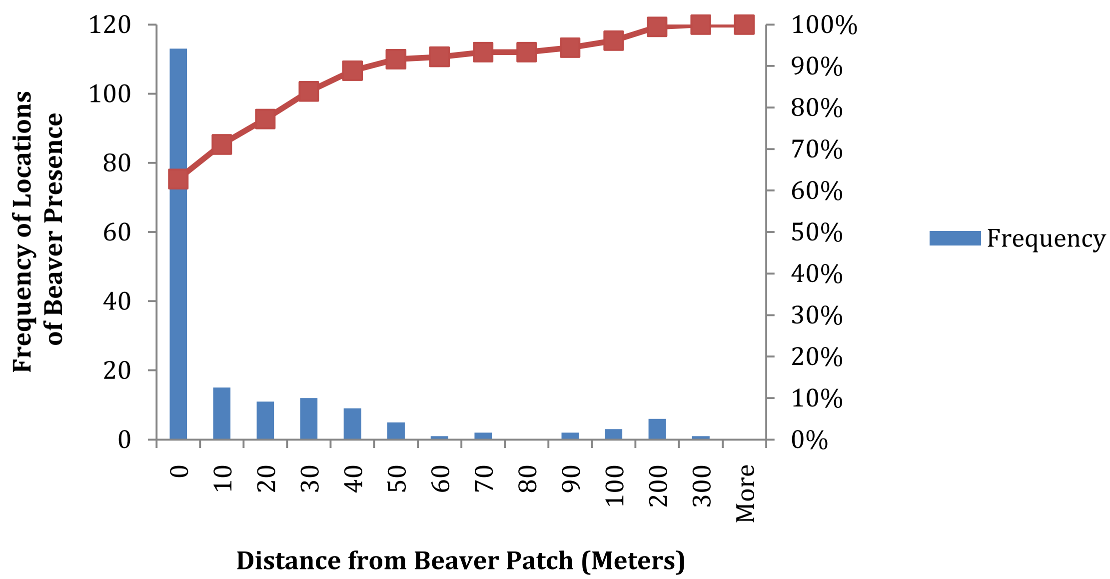


Figure 50. The distribution of geographic distances of locations of current and past beaver presence from the nearest patch. Most locations (114) of beaver presence are within patches (0 m from the nearest patch). However, some locations were greater than 300 m from a patch.

Reference Condition

Establishing the reference condition for beaver abundance or density in the park requires historic data from a comprehensive survey of all watersheds or from surveys based on a well-designed sampling plan. Though much less desirable, reference condition could also be established using data on beaver abundance or density from other locations that are similar to ROMO. Based on the benchmark typology of Stoddard et al. (2006), *Interpreting Historical Condition* may not be available. Instead, the reference distribution used for beaver habitat mapping is based, for the most part, on *Best Professional Judgment*, informed by published empirical habitat studies and incomplete historic survey data from ROMO. The key data limitation was the structural condition of the vegetation. Vegetation structure, as well as composition, is essential for reliable habitat mapping of most wildlife species.

Results/Discussion

To qualitatively assess trends in the beaver population over the past 70 years, we summarized and mapped the data from the surveys in 1939-1940 (Packard 1947) and 1999-2000 (Mitchell et al. (2000) and Mitchell and Ducharme (*unpublished data*); Figure 51). Estimated population was based on the number of active lodges and dens observed. For each active site we assumed a colony of six beavers occupies the site (Packard 1947).

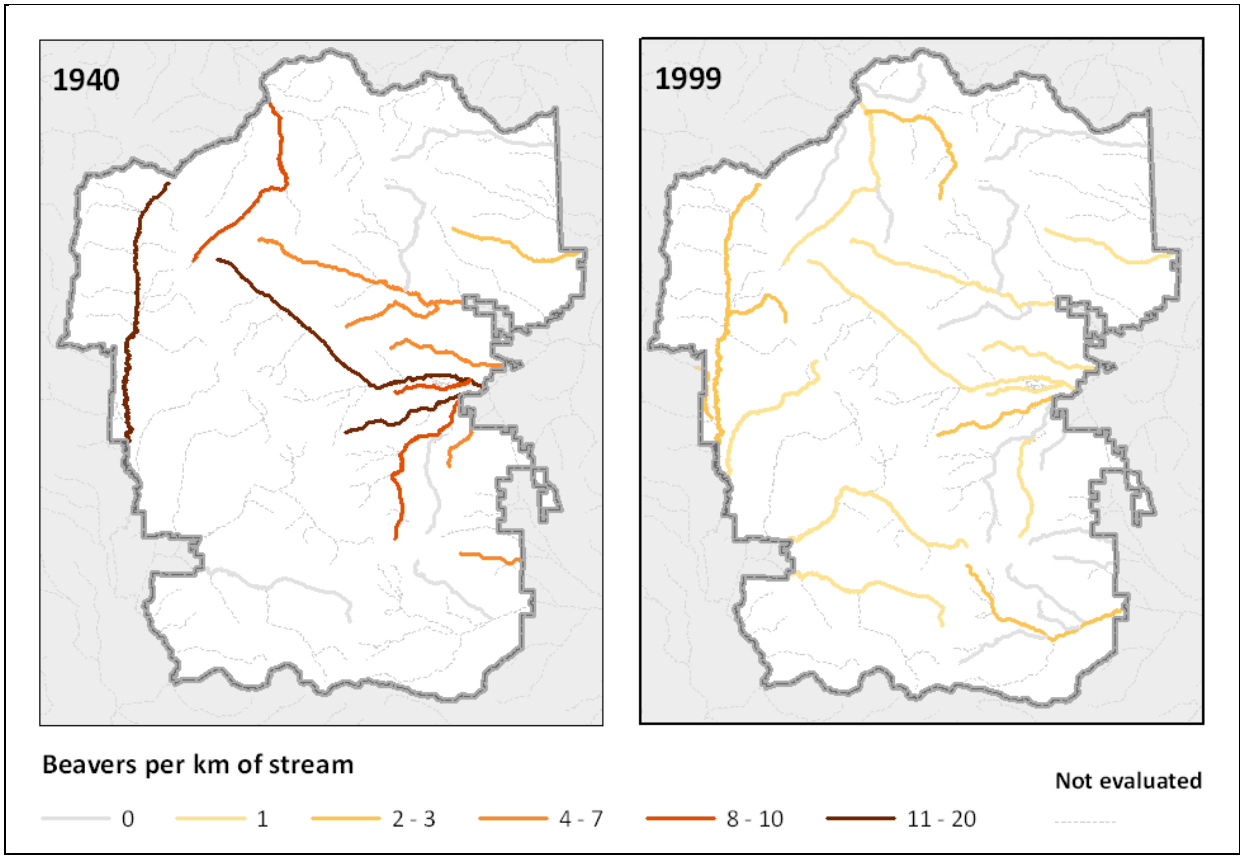


Figure 51. Comparison of beaver densities from surveys in 1939-1940 (left) and 1999-2000 (right) in several drainages in ROMO. Estimates of beaver density from surveys in 1939-1940 are generally much larger than estimates from surveys in 1999-2000. Data attributed to 1:24K stream reaches.

These data suggest declines in beaver populations over that time period, and beaver populations appear to have disappeared from several drainages. The methods used to collect survey data varied between the surveys, but in general, they collected the same kinds of data. Therefore, we suspect the declines in beaver abundance suggested by these surveys are real and not an artifact of different field methods. Based on these surveys and an assessment of willow populations in Moraine Park, Baker et al. (2005) noted declines in beaver populations and a corresponding decline in tall willow over the same time period:

> Beaver were once abundant in the study area but declined dramatically after 1940; for example, population estimates in Moraine Park were 315 in 1939–1940, 102 in 1964, 12 in 1980, and six in 1999. In a comparison of 1937/1946 and 1996 aerial photographs, Peinetti et al. (2002) found that tall willow (> 3 m) cover declined by 54% in Moraine Park and 65% in Horseshoe Park. Short willow plants (< 1.5 m) have dominated the study area for several decades, probably a result of a change in individual plant stature rather than in willow species composition. Thus, beaver and willow populations have both declined in heavily browsed environments within [ROMO].

Mitchell et al. (2000) estimated browsing impact on willows during the 1999 to 2000 beaver survey (Figure 52). Packard (1947) estimated that 600 beaver lived in the Kawuneeche Valley around 1940. Today, beaver are rare in the valley (Rick Scherer, *personal observation*).

Estimates of beaver abundance and density from similar habitat in other locations also tend to be much higher than current densities in ROMO. Baker and Hill (2003) summarized densities reported in the literature and found there to be a wide range in the density of beaver colonies, from near zero to at least 4.6/km^2 (reviews by Hill 1982; Novak 1987). Observers in different regions have attempted to estimate the maximum density or saturation point in local populations. Saturation has been reported to vary from 0.4 colony/km of stream in northern Alberta to 1.2 colonies/km of stream in New York and Utah (reviews by Hill 1982; Novak 1987). In the headwaters of four Alabama watersheds, saturation approached 1.9 colonies/km of stream (Hill 1976). Based on available survey data and other published research, it appears the abundance of beaver in ROMO is far below historic levels.

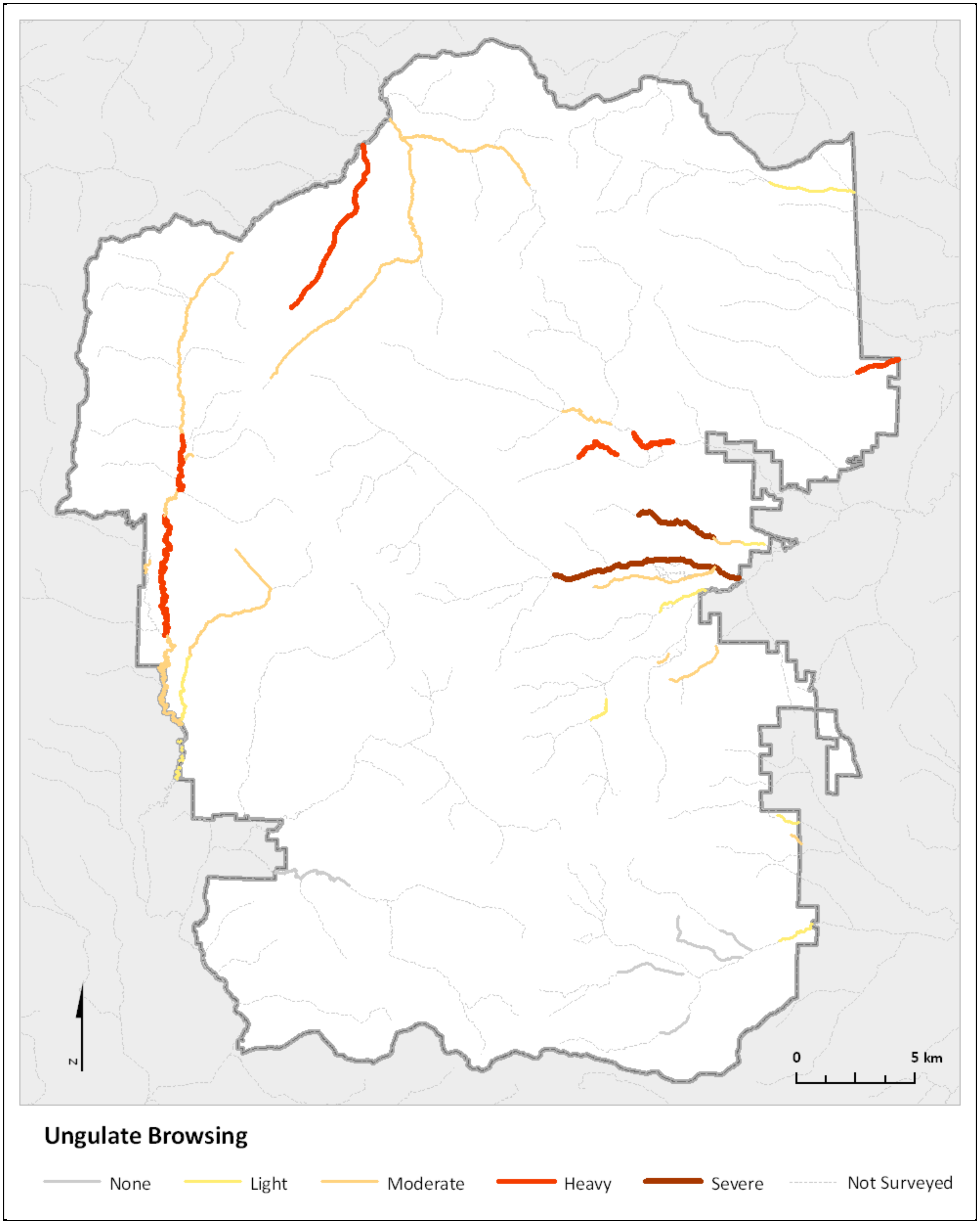


Figure 52. Map showing drainages surveyed in 1999 to 2000 classified based on impact of browsing on willow. Drainages in dashed light grey were not surveyed. Browsing data comes from the 1999 to 2000 beaver surveys conducted by Mitchell et al. (2000).

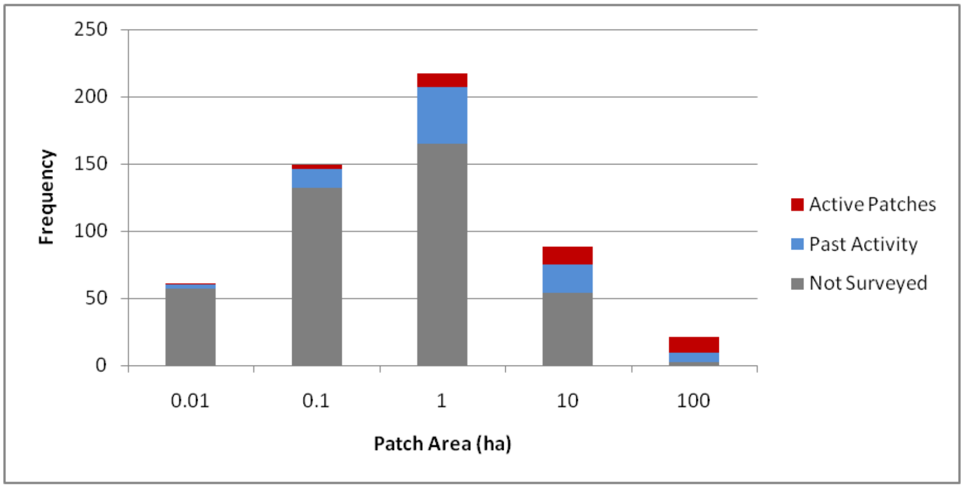
We delineated 536 patches for a total area of suitable beaver habitat of 1,040 ha (about 1%; Table 32). We considered a patch to be active if it contained at least one of the locations of current beaver activity from the surveys of Mitchell et al. (2007) and Mitchell and Ducharme (*unpublished data*). A patch was considered no longer active if it was surveyed and only locations of past beaver activity were observed. Most patches (409) were in drainages or along creeks that were not recently surveyed.

Table 32. Summary statistics for the patches of suitable beaver habitat in Rocky Mountain National Park. Std. Dev. Area and Std. Dev. Suitability Score are the standard deviations of patch area and average patch suitability score, respectively.

Summary Statistics	All Patches	Active	Past	Not Surveyed	No Activity
Number of Patches	536	39	87	409	1
Area (ha)	1040	497	297	244	2
Average Area (ha)	1.94	12.7	3.42	0.6	N/A
Std. Dev. Area(ha)	7.8	21.53	9.6	1.61	N/A
Maximum Area (ha)	93.6	93.6	67.9	18.2	N/A
Avg. Suitability Score	0.43	0.62	0.6	0.37	0.61
Std. Dev. Suitability Score	0.26	0.18	0.24	0.24	N/A

A general principle of ecology is that larger patches of suitable habitat and habitat of higher quality should support larger populations of a species (Hanski 1999). Our data provide further support for the validity of this principle. Higher proportions of large patches (≥ 10 ha) and patches of high quality (high average beaver habitat suitability score across pixels in a patch) contain evidence of current or past beaver activity (Figure 53). One possible reason for the higher proportion of large patches with evidence of current or past beaver activity is that they cover a larger percentage of the study area, and therefore, it is more likely that beaver locations fall within their boundaries.

According to our model and the method we used to delineate patches, most patches of suitable beaver habitat in the park are small (≤ 1 ha; Figure 54) relative to estimates of home range size for beaver. Wheatley (1997) reported home range sizes as large as 18 ha and the results of a modeling project suggest a colony of beaver comprised of 6 individuals requires a minimum of 4 ha for long-term persistence (Baker et al. 2005). Thus, much of the potentially suitable habitat in the park may be in patches that are too small to support persistent beaver populations. Of course, the abundance of small patches of suitable beaver habitat may be an artifact of the method we used to delineate patches. A limitation of the method is that individual suitable pixels were considered part of a larger patch only if they shared an edge or corner with another suitable pixel. Individual pixels that were suitable (had a suitability score greater than 0) but did not share an edge or corner with a neighboring suitable pixel were identified as individual patches. In some cases, patches comprised of a single pixel were near, but not connected to, other suitable patches. While our model considers these pixels to be individual patches, beaver may perceive collections of unconnected, suitable pixels that are near one another as part of a single, larger patch. In fact, our data support this idea. Evidence of recent beaver activity in patches as small as 0.01 ha (one pixel) was observed during the surveys in 1999 and 2000. It is highly unlikely that suitable patch sizes were smaller than our data resolution.



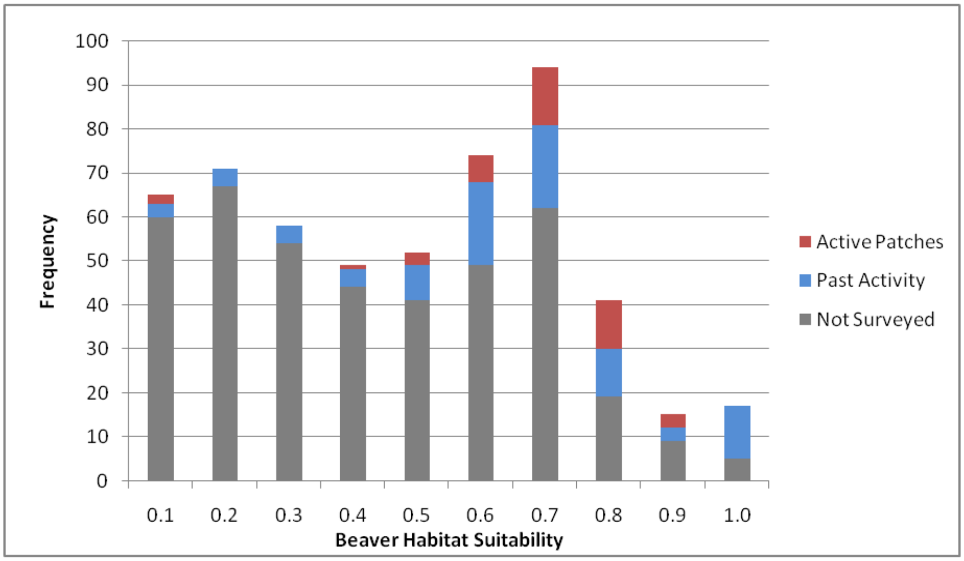


Figure 53. Distribution of size (top) and quality (bottom) for the 536 patches in the study area. The number of patches in each size or beaver habitat suitability class that contains evidence of beaver activity is shown by the portions of each bar shaded in red (current beaver activity) and blue (past beaver activity). The beaver habitat suitability scores in the bottom figure are averages across all pixels that make up each patch. Small proportions of the patches in the smaller size classes and of lower quality contain evidence of current or past beaver activity, while larger proportions of patches in the larger size classes and of higher quality contain evidence of current or past beaver activity.

In general, however, evidence of current beaver activity was found in larger patches with higher average suitability scores (red squares in Figure 54). Examination of the distribution of patch sizes and average habitat suitability scores for patches with evidence of active beaver colonies suggests a minimum patch size of 0.10 ha and a minimum average suitability score of 0.4 for beaver to occupy a patch.

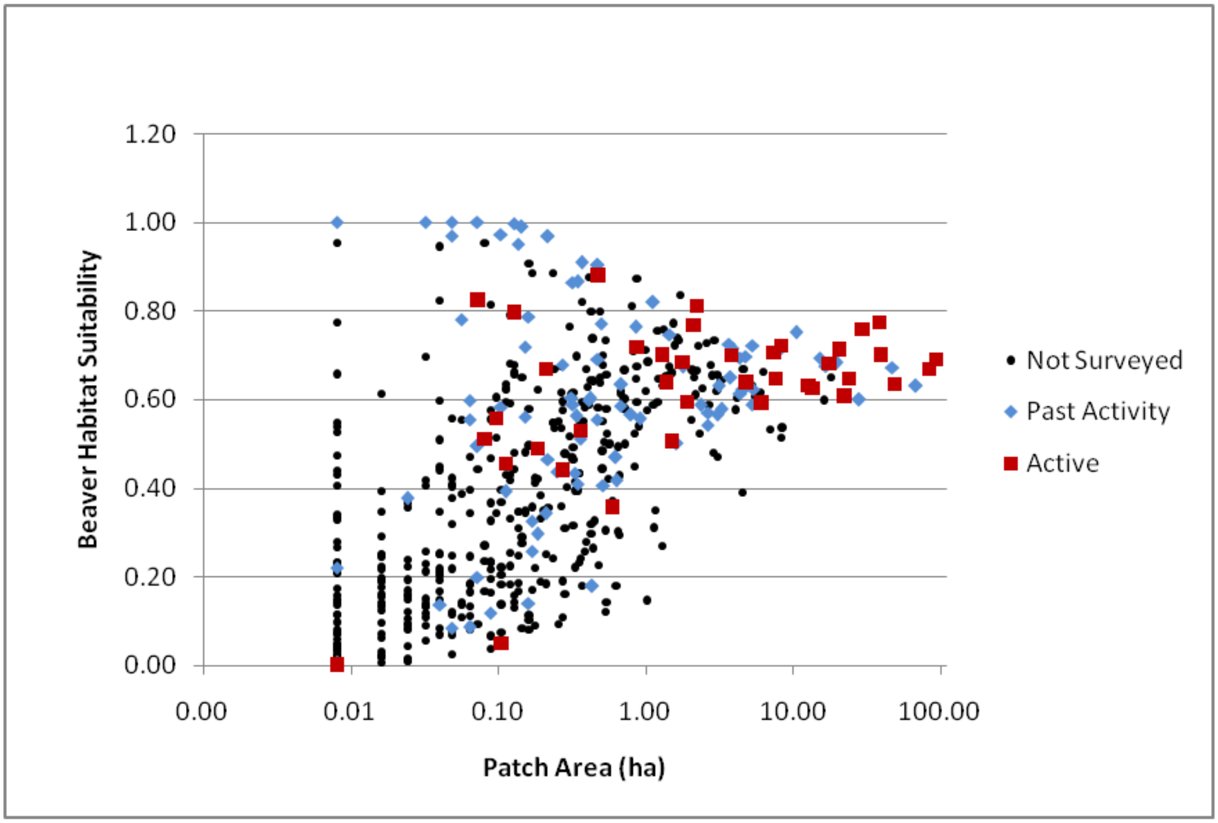


Figure 54. Minimum patch size of 0.01 ha and a minimum average suitability score of 0.4 for locations of current beaver activity.

Potential beaver habitat is not distributed evenly within the park. Our model identified more potential beaver habitat of higher quality in the western half of the park compared to the east. The Colorado River as it flows through the Kawuneeche Valley has the greatest area of potential beaver habitat within the park, estimated at 189 hectares. Two other drainages in the Kawuneeche Valley, Onahu Creek (98 hectares) and Baker Creek (84 hectares) had the second and third highest amounts of potential beaver habitat within the park. On the east side of the park Fall River and the Big Thompson River had an estimated 62 and 56 hectares of potential habitat respectively.

Scenarios for Restoration

Given that the current distribution and abundance of beaver in ROMO is far below historic levels (Figure 51), it is important to prioritize areas for habitat restoration or reintroduction of beaver. We have addressed the question of prioritization in two ways: first, by summing the area of potentially suitable habitat within all HUC-12 drainages in the park; and second, by computing the proportion of a HUC-12 drainage that is potentially suitable beaver habitat. We combined these two ways of evaluating potential for suitable habitat into a map we referred to as restoration potential (Figure 55). The HUC-12 drainages of highest restoration potential are Colorado River-North, Big Thompson River-West, Onahu Creek, Cache la Poudre-South, Fall River, and Glacier Creek.

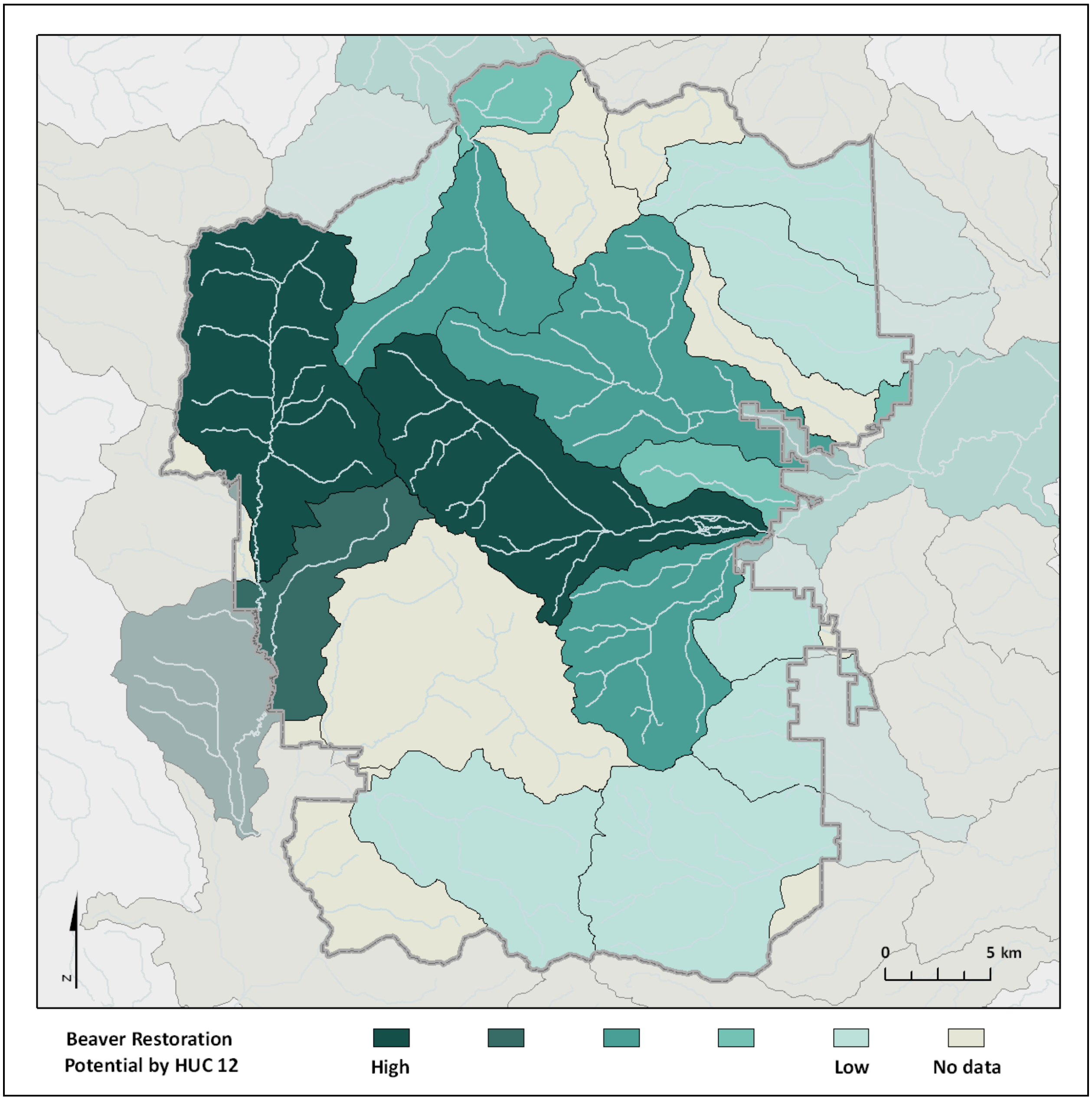


Figure 55. Beaver restoration potential by HUC12. Restoration potential was based on the total area of potentially suitable beaver habitat multiplied by the change in estimated beaver population between 1940 and 1999.

<u>Uses and Limitations</u>

Although the data on beaver locations suggest the beaver habitat suitability map provides a reasonable approximation of the amount and location of beaver habitat in the park, there are a number of caveats that should accompany our research results.

We primarily used data on stream gradient, the slope of the terrestrial environment and the distribution of suitable vegetation and other land cover types to develop the map. Clearly, the set of environmental elements that influence the suitability of an area for beaver exceeds those used to build our habitat model. The results from field studies in other parts of the geographic range of beaver suggest beaver presence is correlated with stream width and depth, the amount of bare ground and other elements of the landscape (Beier and Barrett 1987; Barnes and Mallik 1997). These components were not incorporated into our map because data were not available or were at a spatial resolution that we felt was inappropriate for this project. For example, the map of Salas et al. (2005) contains data on the locations of areas of bare ground in the park. However, Salas et al. (2005) used aerial photo interpretation to classify vegetation and land cover in the park. Consequently, they could only delineate relatively large, contiguous areas of bare ground, so their data were too coarse to be useful in our mapping process.

Despite apparently high levels of interest in beaver by natural resource managers and the general public, there was a surprising lack of information on movement behavior. Radio telemetry is often used to collect movement data on animal species, and problems associated with mounting radio telemeters on beaver appear to be an important cause of this lack of information (Baker 2005). In particular, we lacked information with which to develop more than coarse, general estimates of the relative costs of movement through various habitat types. That is, we were only able to assign costs to pixels based on a coarse assessment of the slope of the pixel and whether the pixel represented a stream or the terrestrial environment. If information becomes available from future studies, it could be incorporated into the mapping process and may improve the utility of the map.

Also, the vegetation map provided little information on willow height, and willow height appears to be an important criterion when it comes to determining beaver use. We used the vegetation map without consideration of the actual height of shrubs. Beaver need taller shrubs for dam and lodge construction.

Beaver use other habitat types besides streams, so our source cells may have been too restrictive.

Due to the limited availability of relevant spatial data and movement behavior in beaver, the final beaver habitat suitability map should be considered primarily a map of potential beaver habitat. This model is a first-run approximation and is likely to include both errors of omission and commission with regard to identifying suitable beaver habitat. A follow-up study to inventory beaver sites would be valuable.

At this point it appears that the amount of suitable habitat in the park may be limited by the area of mature willow stands within riparian areas (Baker et al. 2005). In order for willow stands to develop sufficient girth for dam and lodge construction, elk browsing intensity will need to decrease (Baker 2003, Baker et al. 2005). Thus, at this time the size of the elk population may be indirectly limiting the size of the beaver population through herbivory. Our mapping exercise was unable to discriminate mature willow stands from those heavily browsed by elk. As a result of the extent of elk browsing in willow stands, we have mapped potential habitat rather than currently suitable habitat.

Overall, we believe that this indicator supports a *high degree of concern***,** because of the key role beaver have in riparian ecosystems of the park and the extent and widespread disruption of the hydrologic processes in the park. We rank our level of confidence in this indicator as *moderate/moderate*. We rated this as *moderate agreement*, because some uncertainty remains among experts as to the direct role beaver play in riparian condition. Because of the complicated linkages of riparian condition with other factors such as elk population levels, trapping of beaver, and lack of top predator (wolf), the additive effects of beaver to riparian ecosystems is difficult to estimate. We rated this indicator as *moderate level of evidence*, because this indicator is mapped on consistent landscape data, validated by aerial photography for current (and some historical distributions), and relatively consistent with historical surveys of beaver and expert opinion.

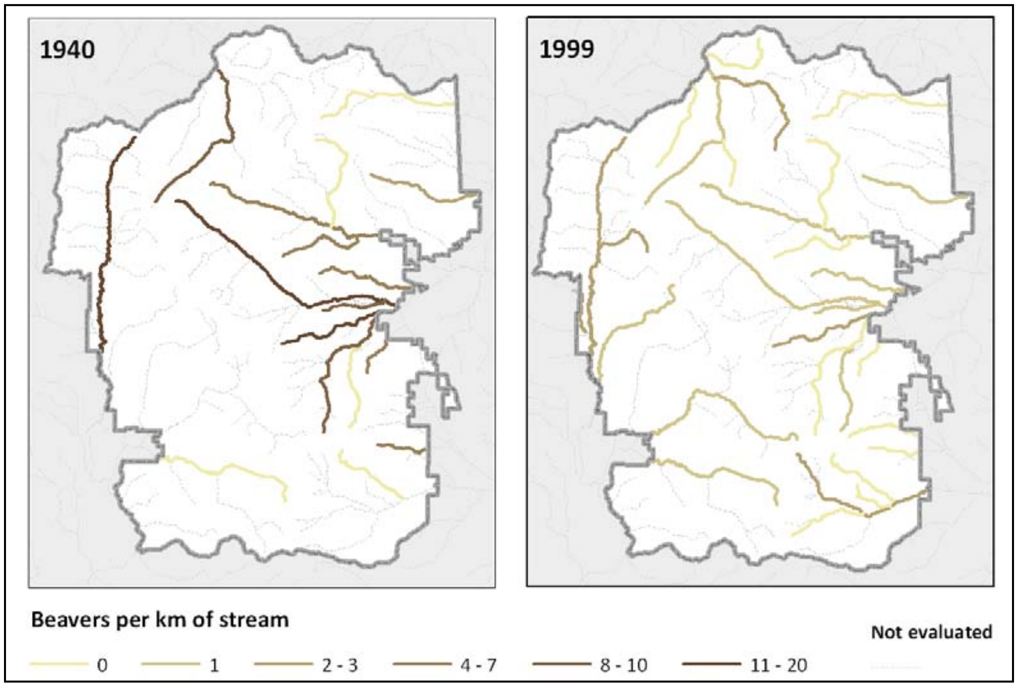
<u>Summary: Biotic Integrity - Extent of Suitable Beaver Habitat</u>

What: Measures the distribution and proportion of potentially suitable beaver habitat and compares it to historical surveys.

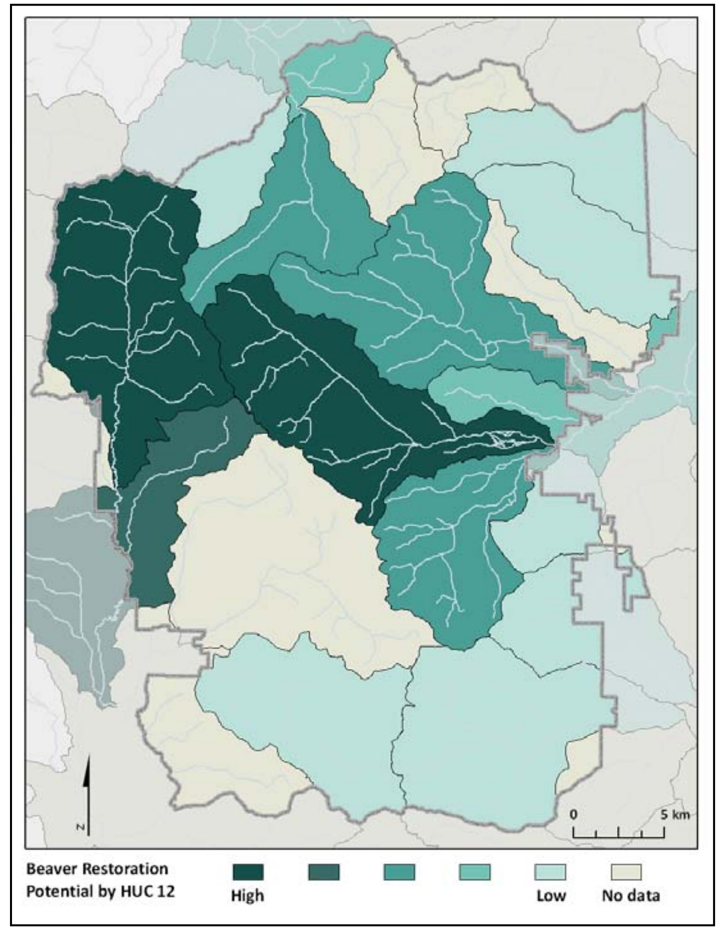
Why: Important to understand the historical role beaver had in riparian vegetation and is critical to understand elk/willow dynamics.

Stressors: Over-abundance of elk, Grand Ditch, climate change

Confidence: High degree of concern; moderate evidence, moderate agreement



The current distribution of beaver is far below historic levels (bottom map). Highest areas for restoration potential (right map) include Colorado River (north); Big Thompson River (west), Onahu Creek, Cache la Poudre (south), Fall River, and Glacier Creek watersheds.



4.2.6 Landscapes: Extent and Proportion of Major Ecological Systems

Authors: Barry R. Noon, David M. Theobald, and John B. Norman, III

Description/Purpose

Here we report on an initial attempt to characterize the landscape of the park in terms of a small set of coarse-filter landscape measurements. These measurements are based on a characterization of the area and spatial arrangement of the dominant vegetation communities of the park at the scale of 12 digit-Hydrologic Unit Codes (Seaber et al. 1987), and in some cases summarized by major watersheds (HUC 8s)—the Big Thompson, Cache la Poudre, Saint Vrain, and Colorado Rivers. This partition of the park into its HUC-12 watersheds allowed us to compare and contrast the metrics developed in this chapter across watersheds to detect similarities and differences at a resolution meaningful to broad-scale ecological processes. There are numerous characterizations that use landscape metrics, such as: Jones et al. (1997, 2001), and Riitters et al. (2002).

Approach/Methods

For this assessment, we used the 2007 LANDFIRE land cover data developed by the Departments of Agriculture and Interior and the Nature Conservancy. We used LANDFIRE because it provides a much finer classification of ecological systems over the National Land Cover Dataset, and is consistent across the full Southern Rockies, whereas the Southwest Regional GAP dataset does not include the northern portion of the Southern Rockies (Wyoming). The LANDFIRE (LF) data have a resolution of 30m and are derived from Landsat Thematic Mapper data and other ancillary data sources. The original LF data recognized 36 land cover categories. To simplify the analysis we reclassified the LF data into 7 categories reflecting major ecological systems found in the park: riparian/wetland, aspen forest and woodland, lodgepole pine forest, lower-, mid-, and upper-montane forests, alpine tundra, and snow and ice (Table 33). We aggregated these 0.09 ha (0.22 ac, 30 m cells) up to 0.81 ha (90m) to filter out finer-scale variation in the data, as well as reduce the computational requirements. Prior to estimating the metrics, the LF coverage was partitioned by the HUC-12 boundaries to generate patch boundaries along watershed boundaries. We did this so that our patch-based metrics reflected watershed boundaries.

Table 33. Listing of the eight major ecological systems from LANDFIRE existing vegetation types, for which we measured the extent and proportion.

Ecological systems	Classes	Dominant types
Alpine tundra	2006, 2070, 2143, 2144	Alpine/montane sparsely vegetated; alpine dwarf shrubland; alpine fell-field; dry turf
Upper elevation forest	2055, 2056, 2057	Dry-mesic spruce-fir forest and woodland; wet-mesic spruce-fir forest and woodland; subalpine montane limber-bristlecone pine woodland;
Mid elevation forest	2011, 2051, 2052, 2061, 2066	Aspen forest and woodland; dry-mesic mixed conifer forest and woodland; mesicmontane mixed conifer forest and woodland; aspen-mixed conifer forest;
Lower elevation forest	2016, 2049, 2054, 2059, 2117, 2119	Pinyon-juniper woodland; limber pine-juniper woodland; ponderosa pine woodland; ponderosa pine savanna; juniper woodland and savanna
Aspen forest	2011, 2061	Aspen forest and woodland; aspen-mixed conifer forest and woodland
Lodgepole pine forest	2050	Lodgepole pine forest
Riparian/wetland	2159, 2160, 2162, 2164	Montane riparian systems; upper montane riparian systems
Savannah/steppe	2062, 2064, 2066, 2072, 2080, 2081, 2086, 2093, 2106, 2107, 2115, 2125, 2126, 2127, 2135, 2139	Mountain Mahogany; Mixed / low/ big Sagebrush; Saltbrush; Mixed Salt Desert Scrub; Lower Montane-Foothill shrubland; Colorado Plateau Sand Shrubland; Montane-Foothill Deciduous Shrubland; Gamble Oak-mixed Montane Shrubland; Juniper Savanna; Ponderosa pine Savanna; Big Sagebrush Steppe; Montane Sagebrush Steppe; Semi-Desert Shrub-Steppe and Grassland; Lower Montane-Foothill-Valley Grassland

We conducted two sets of analyses. The first involved envisioning the landscape as a categorical patch mosaic and used FRAGSTATS 3.3 (McGarigal et al. 2002) with an 8-neighbor rule to identify and determine the boundaries between land cover patches. An 8-neighbor rule eliminated many small patches that would have been formed with a 4-neighbor rule and also ignored any fragmentation caused by local and secondary roads (most of the highway and interstates are 1-2 pixels wide). Although there are potential fragmentation effects of the landscape structure by roads, we decided that in general local and secondary roads do not strongly fragment patches for most ecological processes we were interested in (e.g., wildfire, mammal movement, etc.). FRAGSTATS computes landscape metrics at three scales: individual patches (patch-level), across patches within a patch type (class-level), and across all patch types (landscape-level). A very large number of metrics can be computed with FRAGSTATS but many of these are redundant (e.g., Li and Reynolds 1994, Hargis et al. 1997) and many are difficult to interpret ecologically (Baker 2000). We chose a small set of metrics from among those recommended by Botequilha-Leitao et al. (2006) for conservation planning, and metrics used to compare real with simulated landscapes (e.g., Gardner and Urban 2007). Following patch identification by land cover type and watershed, we computed the following metrics (Table 34):

- percent of the watershed in a given land cover groups;
- number of patches > 1ha;
- weighted mean patch size (across all patches of a cover type); and
- largest patch index.

Table 34. Landscape metrics computed for the Big Thompson, Cache la Poudre, Saint Vrain, and Colorado River watersheds, Rocky Mountain National Park.

Landscape Metric	Equation	Units	Interpretation
Percent of landscape (P)	$= \frac{\sum a_{ij}}{A}(100)$	Percentage	Proportion of the landscape occupied by cover type i
Number of patches (NP)	$= n_i$	Number	Number of patches in the landscape of cover type i
Patch density (PD)	$= \frac{n_i}{A}$ (10,000)(100)	Number of patches/100 ha	Number of patches of land cover type i per 100 ha
Area weighted mean patch size (Sav)	$= \sum_{j=1}^{n} a_{ij}\left(a_{ij}/\sum a_{ij}\right)$	Hectares	Area-weighted mean patch size for land cover type i
Largest patch index (LPI)	$= \frac{Max(a_{ij})}{A}(100)$	Percentage	Largest patch of land cover type i divided by total landscape area

For the most part, the metrics we computed focus on patch size and functions of the patch size distribution. We believe this focus is justified because one of the most clear and lasting indicators of disturbance at the landscape scale is the proportion of the vegetation mosaic. In addition, by substituting space for time we believe there is value among watershed comparisons to provide an initial estimate of the range of natural variability (Landres et al. 1999) in the estimated metrics. Note that as a result of the decisions we made about grain size and number of land cover categories, our focus is not on contemporary human-caused fragmentation. Rather, in this report our emphasis is on the major patterns of landscape heterogeneity that have arisen from natural topographic and edaphic variability, past land-use history, and past disturbance events.

A second analysis was done to generate a cumulative distribution function (CDF) that portrayed the distribution of the area of patches of different ecological systems. We then produced a CDF for HUC-12 watersheds overlapping ROMO versus other watersheds outside the park but within the Southern Rocky Mountain ecoregion (SRE).

Reference Condition

Our approach for the reference condition is to use an *Ambient Distribution*, comparing ROMO to its broader context of the southern Rockies Ecoregion. One challenge with this approach, however, is the relatively few number of watersheds within ROMO, which might result in somewhat rapid jumps in cumulative distribution function values. Note that we tried using LANDFIRE's biophysical setting dataset as a benchmark to compare back to existing vegetation types (current), but there was little observed difference.

Results/Discussion

We provide summaries of results by both the four main watersheds (8-digit HUCs) and HUC-12s constrained to be within ROMO so that they are consistent with other indicators. The HUC-8s varied widely in area within the boundaries of ROMO: Big Thompson 42,091 ha; Cache la Poudre 14,569 ha; Saint Vrain 15,212 ha; and the Colorado River 48,162 ha. The watersheds were similar in terms of percent area by land cover type with all watersheds dominated by upper montane forest (Table 35; range 31.8 - 62.7%). The next most dominant land cover type was alpine tundra (range 14.3 – 20.2%). Less than five percent of any watershed was in wetland or riparian vegetation. Overall, the distributions of patch proportions by cover type were similar across watersheds.

The total number of patches varied widely across watershed ranging from 1999 patches ≥ 1ha in the Big Thompson to 481 in the Cache la Poudre. Correcting for watershed area, patch density (# patches/100 ha) was less variable ranging from 11.5 to 6.1 in alpine tundra to 11.7 to 8.1 in upper montane forest. The distribution of the number of patches by cover type was most equitable in the Big Thompson watershed but dominated by snow/ice, alpine tundra, and upper montane forest in the other watersheds. By patch number and composition, lower montane forest and aspen forest/woodland were the most rare cover types.

Table 35. Summary of class-level landscape metrics by watershed for the areas within ROMO. P-percent of watershed in cover type; NP – number of patches >1 ha; PD – patch density (number/100 ha); S_{av} – weighted mean patch size; LPI – largest patch index.

Watershed	Land Type	P(%)	NP (>1ha)	PD	Sav (ha)	LPI (%)
Big Thompson	Snow/ice	4.4	242	2.6	39.7 (7.9)	0.5
	Alpine tundra	14.3	246	6.1	472.8 (33.2)	3.1
	Upper montane forest	31.8	343	10.2	1768.2 (74.1)	8.5
	Mid-montane forest	5.2	187	3.2	46.8 (8.5)	0.4
	Lower montane forest	3.7	153	3.4	52.0 (7.4)	0.5
	Lodgepole pine forest	18.0	250	6.8	697.5 (42.9)	4.5
	Aspen forest/woodland	13.5	311	9.3	457.4 (25.7)	3.2
	Riparian/wetland	3.5	267	2.6	10.8 (3.6)	0.1
Cache la Poudre	Snow/ice	5.9	99	3.6	37.5 (7.6)	0.9
	Alpine tundra	20.2	143	11.5	149.2 (16.1)	3.2
	Upper montane forest	62.7	115	8.1	6747.2 (228.8)	53.8
	Mid-montane forest	< 1	0	0	---	---
	Lower montane forest	< 1	0	0	---	---
	Lodgepole pine forest	3.3	44	4.1	25.9 (4.5)	0.5
	Aspen forest/woodland	0.1	1	0.3	1.5 (0.6)	0
	Riparian/wetland	4.6	79	1.4	36.5 (10.3)	0.8
Colorado	Snow/ice	7.0	262	3.2	83.5 (13.3)	0.7
	Alpine tundra	11.7	394	10.3	114.3 (11.3)	1.4
	Upper montane forest	43.6	313	8.9	5579.0 (16.5)	22.5
	Mid-montane forest	1.0	47	1.3	23.1 (4.2)	0.2
	Lower montane forest	0.1	4	0.4	0.9 (0.4)	0.1
	Lodgepole pine forest	23.1	196	5.0	2113.5 (99.0)	9.7
	Aspen forest/woodland	2.2	129	3.9	16.8 (3.0)	0.2

Watershed	Land Type	P(%)	NP (>1ha)	PD	Sav (ha)	LPI (%)
	Riparian/wetland	5.8	266	2.2	43.3 (10.4)	0.4
Saint Vrain	Snow/ice	7.2	109	3.8	35.9 (8.0)	0.9
	Alpine tundra	17.7	71	8.2	268.3 (24.0)	5.0
	Upper montane forest	39.9	120	11.7	1318.1 (67.0)	16.7
	Mid-montane forest	1.3	22	1.2	17.5 (4.3)	0.3
	Lower montane forest	0.5	8	0.5	8.6 (2.7)	0.1
	Lodgepole pine forest	14.6	71	5.4	241.6 (25.3)	4.4
	Aspen forest/woodland	11.2	66	5.0	292.5 (25.6)	3.9
	Riparian/wetland	3.9	81	1.9	10.6 (4.2)	0.3

Weighted-mean patch size (S_{av}) and largest patch index (LPI) are good measures of the degree to which a cover type is characterized by large to very large patches. With the notable exception of upper montane forest in the Cache la Poudre watershed, there is very little dominance by large patches for any of the cover types (Figure 56).

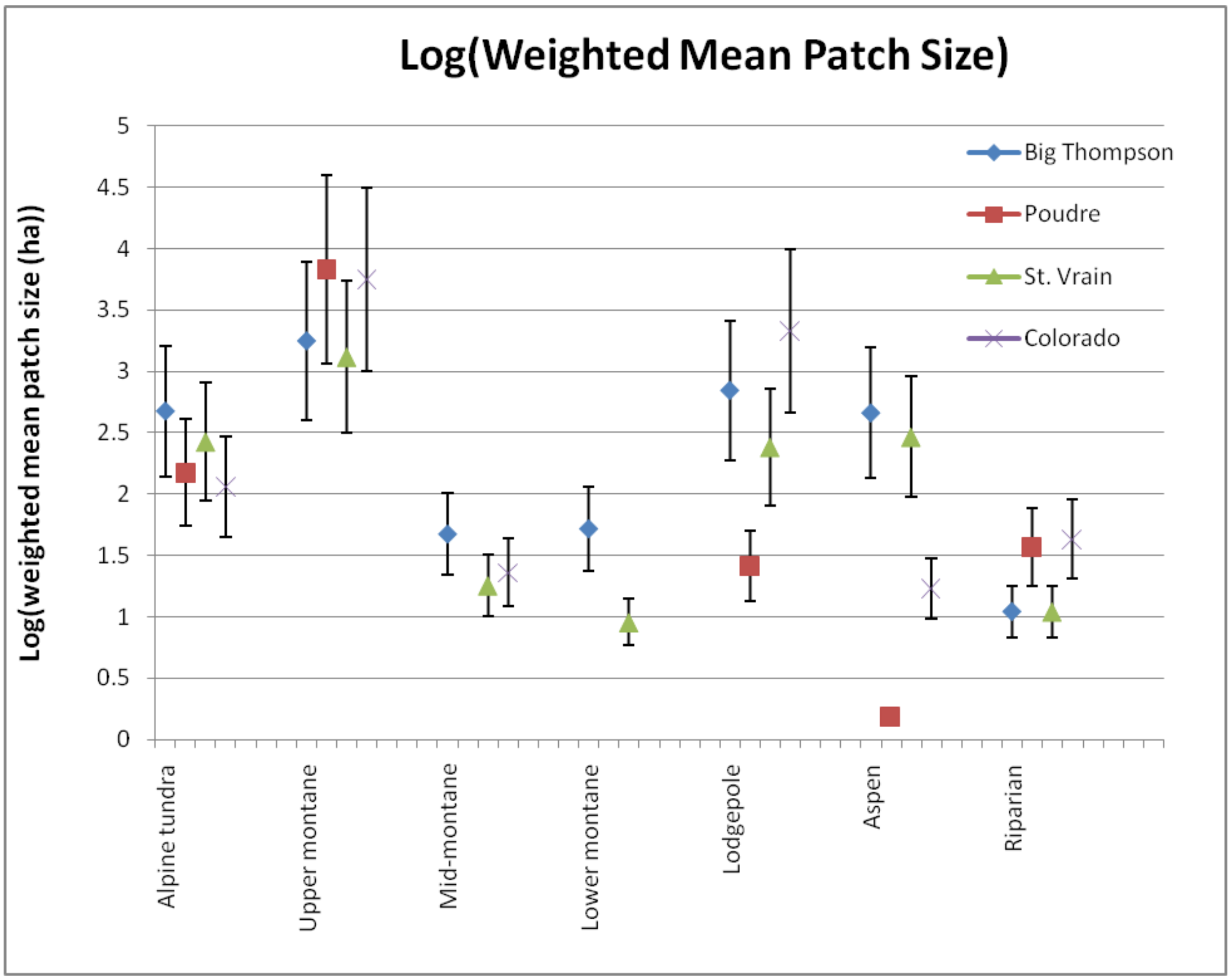


Figure 56. Weighted mean patch size (log10 transformed) by land cover type, by watershed, Rocky Mountain National Park. Error bars are +/- 20% of the mean.

Cumulative distribution functions (CDFs) allow one to easily infer the proportion of patches below (above) a given patch size (Figure 57 and Figure 58). For example, about 60% of aspen patches in the park are < 100 ha. Comparison of CDFs by cover type across watersheds shows that the watersheds are mostly similar in their patch size distributions. The Colorado River watershed is somewhat distinct from the others in having fewer small and more large patches for all cover types. Comparing the CDF between the park and SRE (Figure 57 and Figure 58), we found that the park and the southern Rocky Mountain ecosystems were similar in their patch size cumulative distributions. There was some indication that there were more large patches of high elevation forests, especially lodgepole pine and riparian vegetation within the park. Based on these analyses, and an assumption that patch sizes are a product of mostly natural disturbance events, we conclude that ROMO does not deviate substantially from the broader southern Rocky Mountain ecoregion to which it belongs.

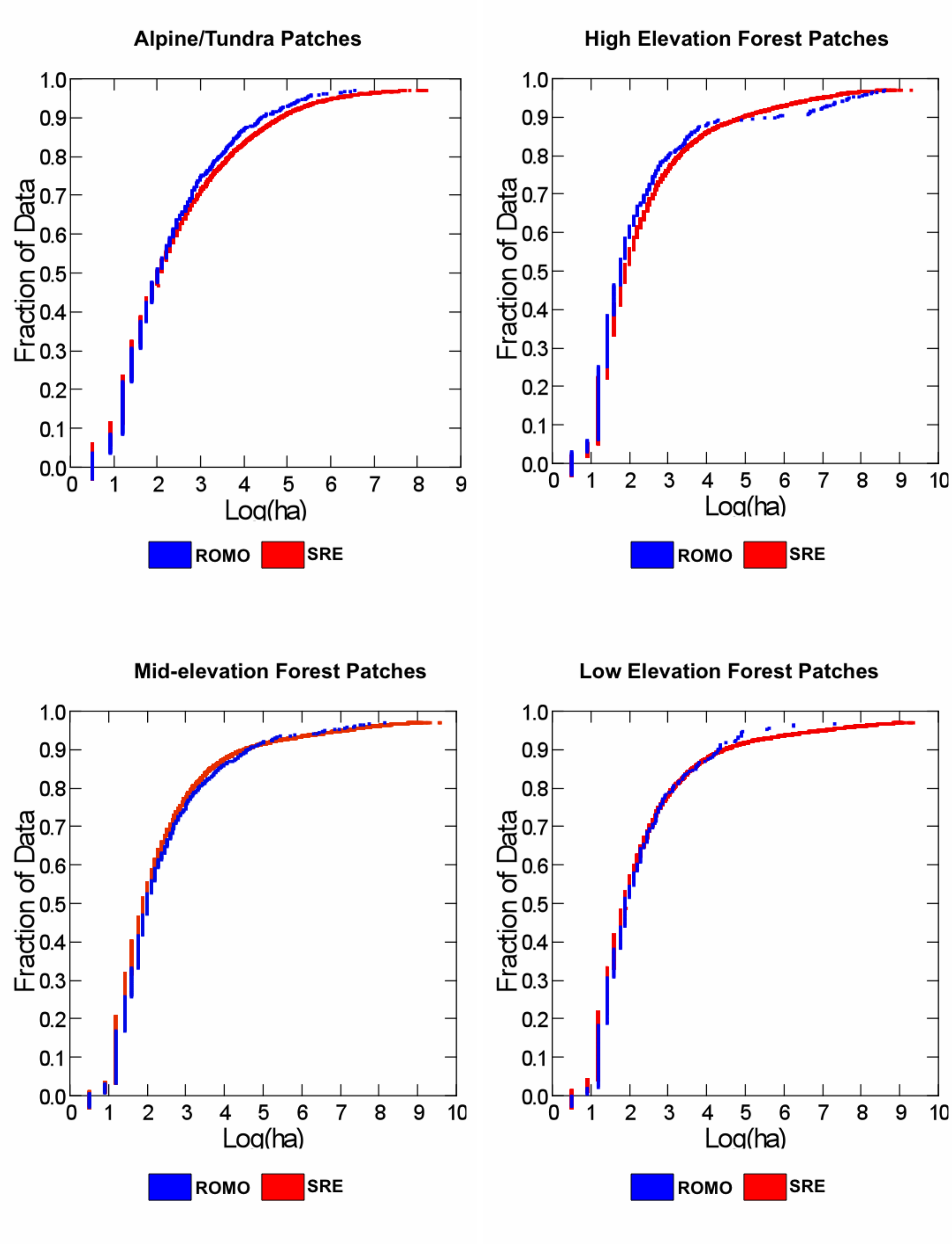


Figure 57. Cumulative distribution functions comparing patches found inside the park vs. outside (but in the southern Rockies Ecoregion): Alpine/Tundra, High Elevation Forest, Mid-elevation Forest, and Low Elevation Forest.

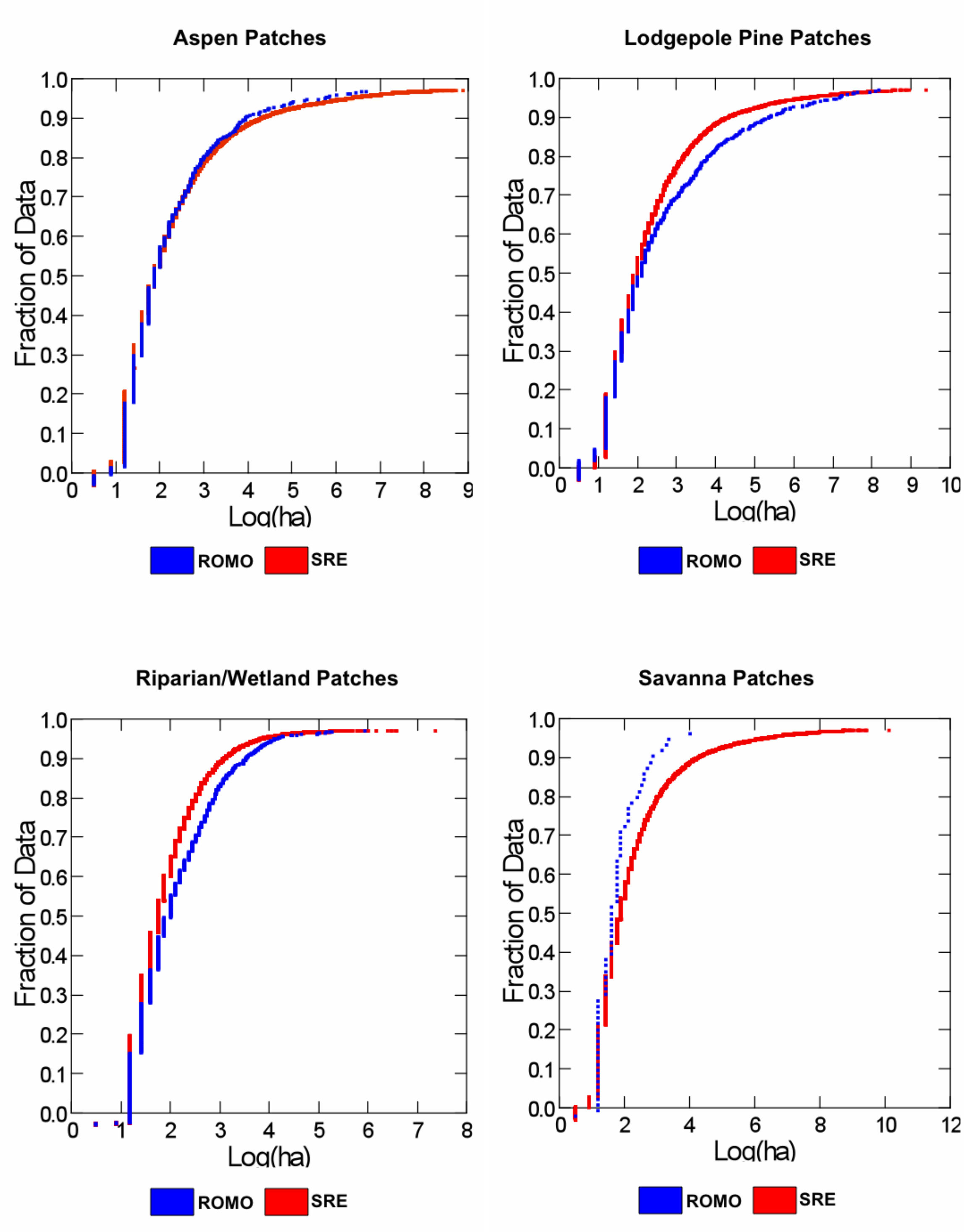


Figure 58. Cumulative distribution functions comparing patches found inside the park vs. outside (but in the southern Rockies Ecoregion): Aspen, Lodgepole Pine, Riparian/Wetland, and Savannah.

We also compared the weighted mean patch size (WMPS) values between SRE and ROMO (Table 36). WMPS weights large patches more heavily than small patches. The result is that the WMPS estimates are skewed in favor of large patches which may have greater ecological importance than small patches. In general, WMPS are smaller in ROMO than in the SRE, except for upper- and mid-elevation forests. It is difficult to provide a clear causal explanation for these differences, which may be a consequence of differing disturbance histories.

Table 36. Weighted mean patch size values between SRE and ROMO.

Ecological system	Weighted mean patch size (ha)	
	SRE	ROMO
Alpine tundra	654	180
Upper elevation forest	1,868	2,600
Mid-elevation forest	2,873	1,205
Low-elevation forest	3,140	443
Aspen	1,311	262
Lodgepole	2,114	1,293
Riparian/wetland	44	48
Savannah	3,146	15

Creation of patch maps from classified imagery is a function of pixel size, the number of land cover categories recognized, and the neighborhood rule used to define patch boundaries. Our results must be viewed in the context of the decisions we made on resolution, reclassification and the 8-neighbor patch geometry.

Extensive heterogeneity or patchiness appears to be the rule for the dominant cover types in ROMO. There are two main sources of heterogeneity that led to vegetation patchiness—these are environmental heterogeneity and disturbance history. Environmental heterogeneity in ROMO is the result of changes in climatic variables along steep and extensive elevational gradients, sharply contrasting slope and aspect positions, variable soil and substrate conditions, and variable moisture conditions at local (differing aspects) and regional (east and west of the Continental Divide) scales. These physical attributes of the park are differentially aligned with the fundamental niches of the dominant plant species resulting in fine scale heterogeneity and patchiness (see discussion in Knight and Reiners, 2000).

Variable disturbance regimes add to environmental heterogeneity and contribute to vegetation patchiness. The main disturbance factor in the forests of ROMO is probably fire (Veblen et al. 1994) and it differentially affects various plant communities. For example, the continuous distribution of fuels in upper montane (spruce/fir) and lodgepole forests predispose these forests to stand-replacing or crown fires. In contrast, most fires in lower montane forests (dominated by ponderosa pine) are surface fires carried mainly by grass fuels (Veblen 2000). Disturbance by fire also varies in its return interval and this in turn varies by forest type. Lower montane forests experience light understory fires every 5-40 years (Veblen 2000). In contrast, upper montane forests experience stand-replacing fires about every 100-500 years (Veblen 2000). Patch size varies as a consequence of what components of the stand are removed by fire (e.g., crown or understory and crown) and the return interval. Thus, we would expect upper montane forests and lodgepole pine forests to be characterized by large, even-aged patches. On the other hand, lower montane forest should be characterized by numerous small patches. In general, this pattern was apparent in the LANDFIRE data set.

Other disturbance factors such as insect outbreaks (e.g., mountain pine beetle, spruce beetle, and western spruce budworm) and windthrow also contribute to vegetation patchiness. Currently, lodgepole pine forests (and to a lesser degree ponderosa pine forests) on the Colorado River watershed are experiencing a significant mountain pine beetle infestation (Sibold et al. 2007), particularly around Grand Lake on the west side of the Park. Based on its extent and the pattern of mortality, this infestation should result in the production of large, continuous patches of lodgepole pine in the future. In general, if a disturbance event is both spatially extensive and results in the mortality of canopy dominant vegetation, large patches should be produced. On the other hand, small, frequent disturbances that only infrequently lead to mortality of dominant vegetation will result in many small patches. It is a tenable hypothesis that the patterns we observed in the patch-size distributions reflected these differential disturbance processes.

By substituting space for time, the comparison of landscape metrics among watersheds provides an initial estimate of the range of natural variability in the environment. For the park, this range of variability appears to be very narrow since watersheds were most notable for their similarity in land cover composition and patch-size distributions and not their differences. It is highly likely that these watersheds would begin to show more extensive differences if lower elevation sites with greater human disturbance were included in an analysis.

Our analyses did not account for fragmentation arising from roads and developments, except for major highways and dense urban areas that are mapped in the LANDFIRE dataset. However, in ROMO these influences are relatively minor and restricted to the community of Estes Park and Trail Ridge Road. Subsequent development of human infrastructures will inescapably lead to greater fragmentation, particularly to lower montane plant communities. We believe that most of the variability in patch size distributions in ROMO is not the consequence of human-induced fragmentation. Rather, we believe that the observed patchiness of the landscape is due to past natural disturbances and topographic variability. Variation in elevation, slope, aspect, and edaphic conditions probably contribute extensively to vegetation heterogeneity in ROMO.

Uses and Limitations

Overall, we believe that this indicator supports a *low degree of concern*. Our level of confidence in this indicator is *moderate/low*. There is *moderate agreement* among experts that the extent and proportion of ecological systems is a valuable way to characterize a landscape, but there is less agreement on how this is interpreted in terms of ecological health.

Summary: Landscapes - Extent and pattern of major ecological systems

What: Landscape metrics that characterize the extent and pattern of major terrestrial ecological systems using LANDFIRE existing vegetation types.

Why: These provide the landscape context of major ecological systems.

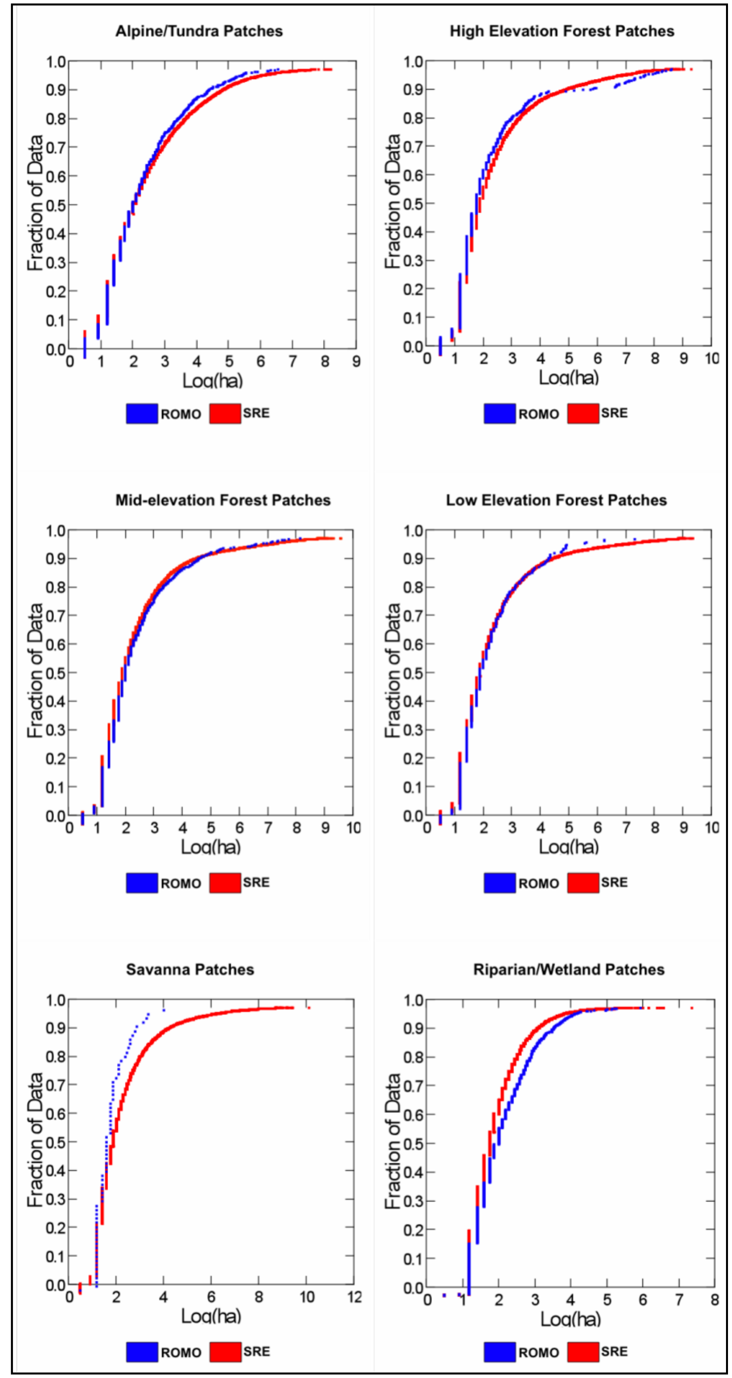
Stressors: Visitor use, land use change, climate change, exotics

Confidence: Low degree of concern; low evidence, moderate agreement

Generally the extent and pattern of patches within the park are similar to those found within the broader Southern Rockies Ecoregion (SRE), although there was some indication that the park contains more large patches of upper elevation forest, but smaller patches of alpine tundra, mid- and low-elevation forest.

Measure	Vegetation Type	Reference Condition (SRE)	Current Condition (ROMO)
Weighted mean patch size (ha)	Alpine tundra	654	180
	Upper-elevation forest	1,868	2,600
	Mid-elevation forest	2,873	1,205
	Low-elevation forest	3,140	443
	Aspen	1,311	262
	Lodgepole	2,114	1,293
	Riparian/wetland	44	48
	Savannah	3,146	15

[1]Patches are defined by 12-digit HUC boundaries and contiguous (8 neighbor)



4.2.7 Landscapes: Connectivity of Natural Landscapes

Author: David M. Theobald

Description/Purpose

An important research challenge for ecology and conservation science is to better understand how land use changes and other human modifications affect the flow of ecological processes and movement of species across a landscape (Taylor et al. 1993). Landscapes have been and continue to be modified by humans, particularly intense human land uses beyond the urban fringe that occupy 10-20% of the U.S. (Theobald 2001). These lands form the landscape context for most parks and protected areas. Natural resource managers in particular have a clear and immediate need to examine landscape connectivity issues. For example, the challenges presented by changing landscapes surrounding protected lands have been identified as a top priority issue by public land managers (GAO 1994; Bosworth 2004; Fancy et al. 2009). These landscape changes around and within a park provide key information especially to better understand how a park is connected into a broader network of protected areas (e.g., Rosenberg et al. 1997; Quinby et al. 2000; Goetz et al. 2008), what adjacent areas are most likely to be used for broader ecological flows into and out of a protected area (Hansen and DeFries 2007), and what the likely consequences of ongoing land use change and transportation fragmentation might be (WGA 2008). The effects of land use have increasingly been a concern to ecologists (Dale et al. 2000, Brown et al. 2005, Theobald et al. 2005, Hilty et al. 2006), particularly the effects on connectivity for species of conservation concern in the western U.S. (Chetkiewicz et al. 2006, Beier 2007).

In addition to general purpose metrics, specific composite indices have been developed to characterize the effects of human activities, such as maps of “wildness” or “remoteness” (Lesslie et al. 1988; Kliskey 1998; Aplet et al. 2000) and the human footprint (Hannah et al. 1995; Sanderson et al. 2002; Leu et al. 2008; Woolmer et al. 2008). Typically, these efforts combine mapped attributes on human population density, land cover, roads, and utility infrastructure. Although these maps have found broad application, the interpretation of the index values is challenging because the ranked scores of several factors, which are created by converting raw values (e.g., people/ha) through arbitrarily defined classes, are combined to generate a composite index. These indices are difficult to interpret because they have no physical interpretation and because the classed values typically violate the additivity axiom (Schultz 2000).

The natural landscapes indicator described here builds on work that evaluated temporal changes in forest fragmentation (Wickham et al. 2008; Riitters et al. 2009) and measures “naturalness” of a landscape -- or conversely, the degree of human modification. “Natural” landscapes are characterized by a high proportion of natural land cover types (i.e. forest, grassland, wetlands), as opposed to human-dominated types (i.e. urban/built-up, agricultural, roads). This approach incorporates data on land cover modifications including presence of roads, human activities associated with developed land use and road use (traffic), and how the broader landscape context modifies local conditions. As such, it does not model the movement of a particular species, but rather provides a general indication of the permeability of a landscape. This indicator assumes that, in general, animals avoid human-modified lands – which is a reasonable assumption particularly for species that were identified by the park managers to be of interest for broader, landscape connectivity (i.e. Canada lynx, mountain lion, and gray wolf).

Approach/Methods

The *Natural Landscapes (NL)* metric estimates the proportion of natural cover I at a location (e.g., a raster cell), which can be loosely interpreted as the probability p that it is natural (or probability that it serves as habitat). The likelihood that a given cell p_c will be influenced by one of its neighboring cells i is the product of the proportions ($p_c p_i$):

$$I_j = \sum_{i}^{n} p_i p_c \Big/ n$$

where p_c and p_i are the proportions of a land cover class in the center and neighboring cell (8 neighbors), at resolution or level j with $j=1\ldots k$. This follows Jaeger's (2002) interpretation of m_{eff} approximating the joint probability of use between two adjacent patches. Note that the center cell c is included in the neighborhood of i to n cells, so n=9.

To generate an integrated, multi-scale metric, I_j is integrated across neighborhoods using a hierarchical, multi-level method where I is computed at each scale j, then aggregated using a 3x3 window to compute the mean value at a coarser resolution (I_{j+1}), and so on until j=k. Here the resolution at j=1 is 270 mI was computed using a logarithmic progression of neighborhood sizes (after Riitters et al. 2002) so k=6: 7.3, 65.6, 590, 5,314, 47,829, and 430,467 ha. Once I_j is computed for each neighborhood, the simple arithmetic mean is calculated across all scales at the finest resolution (j=1, 270 m), which is called the *Natural Landscapes (*NL) metric:

$$NL = \sum_{j=1}^{k} I_j \Big/ k$$

This provides a computationally efficient way to incorporate both local and broad-scale structure into a comprehensive metric whose values rise monotonically from 0.0 to 1.0 with decreasing human modification. Because NL integrates the proportion of naturalness at different scales, it characterizes both compositional and structural aspects of the landscape and measures structural connectivity at a broad, landscape level. Note that the effective weighting at each level j (fine to coarse) is 29%, 24%, 18%, 14%, 10%, and 5% because the neighborhoods are cumulative rather than incremental.

There are four sources of data that were used to generate the NL metric for ROMO: 1) land cover; 2) housing density; 3) roads; and 4) highway traffic volume. The selection of these surrogate variables is supported by Woolmer et al.'s (2008) finding that the three most important variables of impact were land use/cover, human settlement, and roads.

For land cover, I used data from the Multi-Resolution Land Characteristics Consortium's National Land Cover Dataset Retrofit Land Cover Change Product (NLCDr; Fry et al. 2009; www.mrlc.org). This product was developed using a consistent processing method specifically designed to capture land cover changes between 1992 and 2001. The major NLCDr cover types were assigned a value of 1 for each 30 m pixel of "natural" cover types and a value of 0 to "human-modified" types (Table 37). Note that in the NLCDr most major roads (interstates, highways) are classified as urban/built-up as an artifact of the classification process. These artifacts are particularly problematic in rural areas, so the NLCDr data were reprocessed to replace cells classified as urban/built-up with adjacent natural land cover types. Note that most secondary and local roads in rural areas tend not to be classified as urban/built-up in the NLCDr data.

Table 37. Assignment of natural/human-dominated values for each National Land Cover Dataset (retrofit) class. The land cover types water (rivers, lakes, and reservoirs, oceans) and barren (which can be both natural rock/talus in alpine tundra areas) – and were coded as "no data" to exclude them from the analysis, because there is ambiguity between reservoirs and lakes, and tundra and mining.

Class	Anderson Level I Code	Natural/ Human-dominated
Water	1	No data
Urban/built-up	2	0
Barren	3	No data
Forest	4	1
Grassland/shrubland	5	1
Ag (cropland)	6	0
Wetlands/riparian	7	1
Snow/ice	8	1

Land cover modifications associated with low-density residential housing (<1 unit/ha) were not captured in the urban/built-up class of NLCDr (Theobald 2001; Irwin and Bockstael 2007) but have important and widespread effects on habitat and ecological processes (Theobald et al. 1997; Hansen et al. 2005; Merenlender et al. 2009). Consequently, I incorporated data on housing density by finding the minimum value of the proportion of natural land cover (I_1) and amount of human modification of habitat caused by residential development. Commonly, the extent of human modification is estimated as a 100 m radius buffer around each housing unit (Theobald et al. 1997; Gonzalez-Abraham et al. 2007), but here I used empirical estimates of the "footprint" of land cover modifications that was visible from aerial photography around each housing unit (Leinwand 2009): 4.65, 2.65, and 0.33 ha per unit for rural (<1 unit per 16 ha), exurban (1 unit per 1 to 16 ha), and suburban/urban (>1 unit per 1 ha) densities. To calculate *NL* for 1992, I adjusted the NLCDr values by the human modification associated with housing density for 1990. Similarly, I adjusted the 2001 NLCDr using housing density for 2000. To approximate future conditions, I used housing density that was forecasted for 2030 (see Theobald 2005 for detailed methods) with NLCDr for 2001. Because predicted land cover data in 2030 do not exist, land cover types remained static from 2001 to 2030.

I incorporated further likely reductions in "naturalness" due to the presence of highways, secondary, and local roads. This was estimated by measuring the footprint (road and adjacent disturbed area) visible from aerial photography to estimate the proportion of a 30 m cell that was affected by different road types from the Streetmap 2006 database (ESRI 2007): interstates and state highways 100%; secondary roads 50%; local roads 30%; 4WD roads 10%. Because incorporating the effects of road use, not just presence, is important (Forman & Alexander 1998; Chruszcz et al. 2003; Alexander et al. 2005), I included further reductions of naturalness from likely disturbance near highways from traffic (Jaeger et al. 2005). I used data on highway traffic volume measured by the annual average daily traffic (AADT; USDOT 2007). I then applied a quadratic kernel density filter to generate a “smoothed” traffic volume raster, *s*, reflecting the assumption that the impact declines with distance out to 1 km away from a road (based on Forman & Alexander 1998). The proportion of habitat loss from highway use *r* was computed as a non-linear function of the smoothed AADT values:

$$-$$

For example, the impact *r* for a cell on a highway with AADT ≥10,000 is 1.0, while an AADT of 5,000 is 0.71 and AADT of 100 is 0.1. For a cell that is 1 km or more from a highway, regardless of its use level, *r* = 0.0. Although the form of distance-decay and level of impact is arbitrary, it is based on general findings from road ecology on the distance decay effects from vegetation modifications, additions of materials and chemicals (e.g., salt), changes to hydrology, generation of noise and light, and habitat collisions (Forman et al. 2003, pg. 308). I also incorporated habitat loss due to the presence of active railways, *t*, by assuming the impact was 0.5 on 270 m cells that intersect railways and declined to 0.0 at a distance of 1 km (because we do not have data on rail use, here we are estimating only the effect of railway presence). The incremental models do not assume a cumulative effect; rather I make the conservative assumption that the degree of human modification is the maximum effect of any one dataset.

I examined the landscape dynamics of the ROMO by calculating *NL* for recent (1992), current (2001), and near-term (2030) conditions, and I summarized NL scores by the ROMO boundary and the Southern Rockies Ecoregion (Bailey 1995). Note that we did not summarize this indicator by watershed here, because this metric characterizes patterns that are much broader than the watersheds (HUC12) that were used to summarize patterns within the park.

Reference Condition

The approach for the reference condition for this indicator was to use the *Best Professional Judgment* method to identify the weight values for the human-modified metric. From these metric values computed both within the park and for the broader Southern Rockies Ecosystem (SRE), the *Ambient Distribution* computed for the SRE was computed to characterize how the park compares to its broader context.

Results/Discussion

As expected, the NL metric values indicate that ROMO is a highly natural setting, with a mean value of 0.9577 in 1992 and 0.9555 for 2001 (Figure 59). Within the park, some fine-scale variation can be seen, such as roads (Trail Ridge Road), but in surrounding areas where much more human-modification has occurred there are more patterns visible, such as adjacent highways (e.g., US-34 to Estes Park). The mean NL value for ROMO has declined slightly in the past from 0.9577 to 0.9555 from 1992 to 2001 (Figure 60), and will likely decline further to 0.9471 by 2030 (Figure 61). This corresponds (roughly) to a loss to the park of 237 ha by 2001 and an additional 903 ha due to forecasted housing growth outside the park by 2030.

Park and ecoregional scores can be compared to understand the immediate ecological context (Figure 62): e.g., Rocky Mountain’s score is about 0.026-0.030 above its ecoregion and declining over time: but the decline in ecoregional NL value (0.0075) is roughly 3 times the decline for the park (0.0022) from 1992 to 2001.

Compared with other national parks, ROMO is set within a fairly natural context, compared to Delaware Water Gap (0.6431) and Yosemite (0.9520), but Yellowstone is slightly better (0.9749). Landscape change surrounding a park is readily quantified over time with NL in anticipation of residential growth in nearby areas.

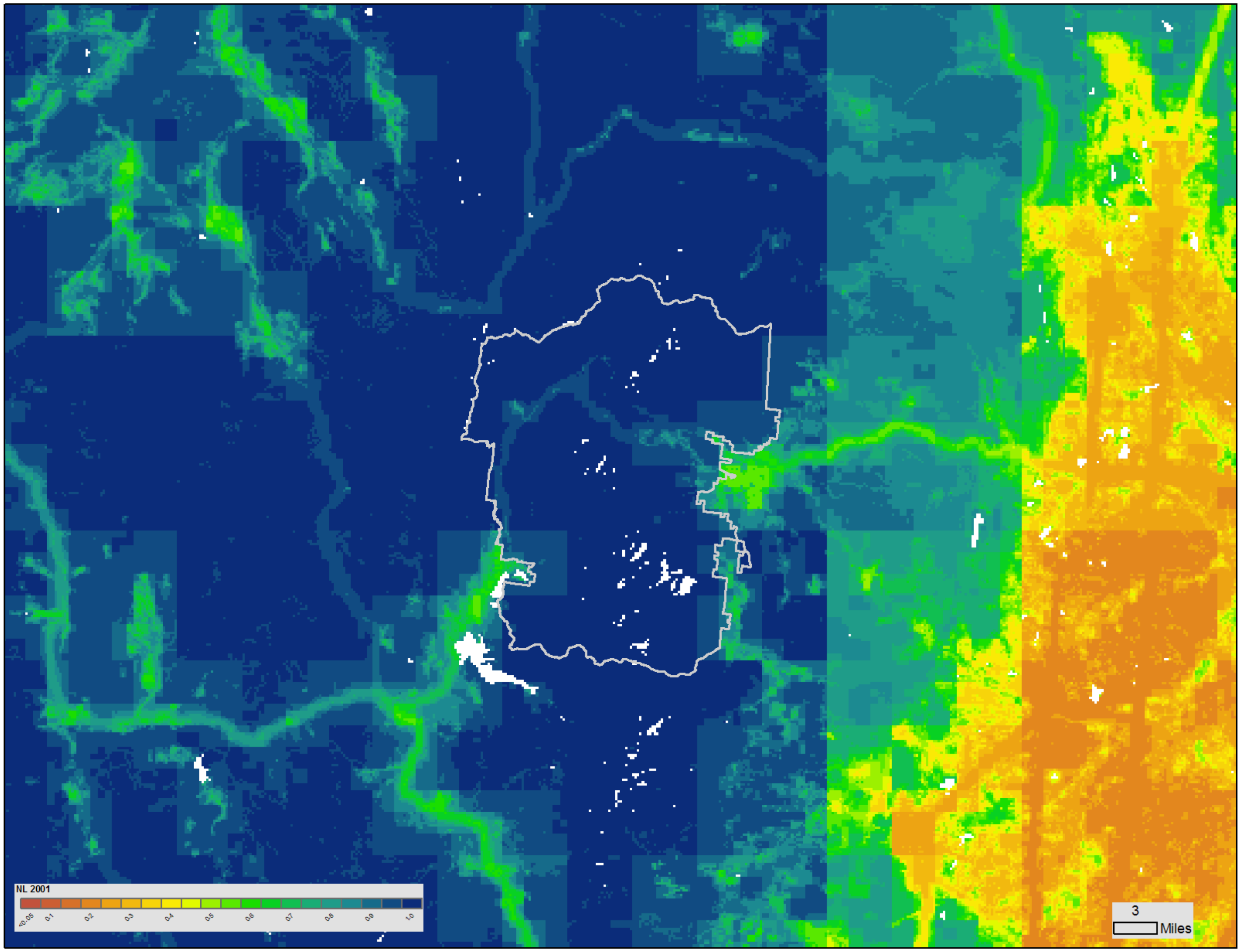


Figure 59. Natural landscapes (NL) metric values in 1992 for Rocky Mountain National Park, Colorado (in center of image, boundary shown in black). The mean NL value is 0.9577 – with high values in blue, low values (highly-modified) in yellow/orange, and water/snow as white (NO DATA).

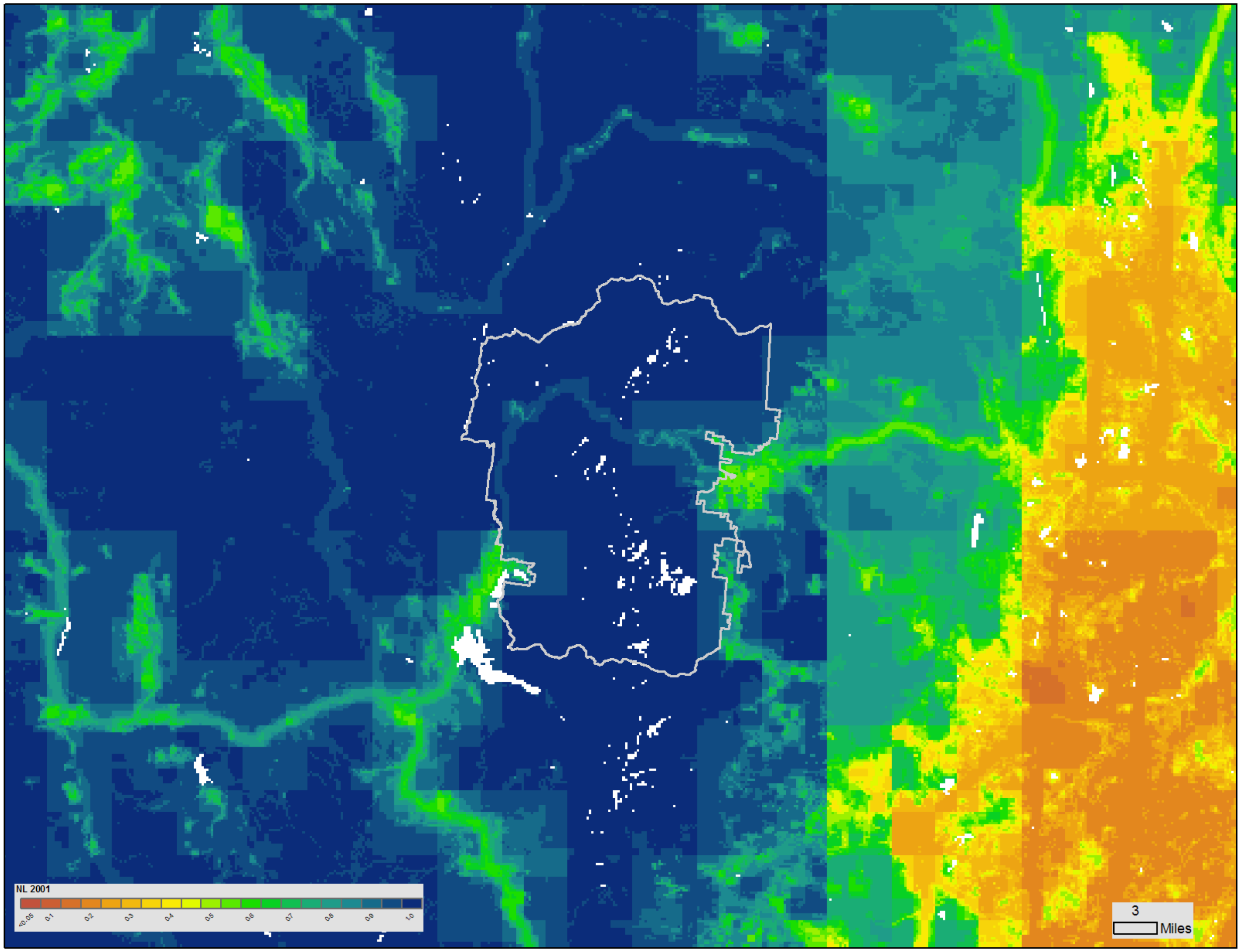


Figure 60. Natural landscapes (NL) metric values in 2001 for Rocky Mountain National Park, Colorado. The mean NL value is 0.9555 – more natural landscapes are shown in blue, while highly-modified landscapes (low values) are shown in orange/red.

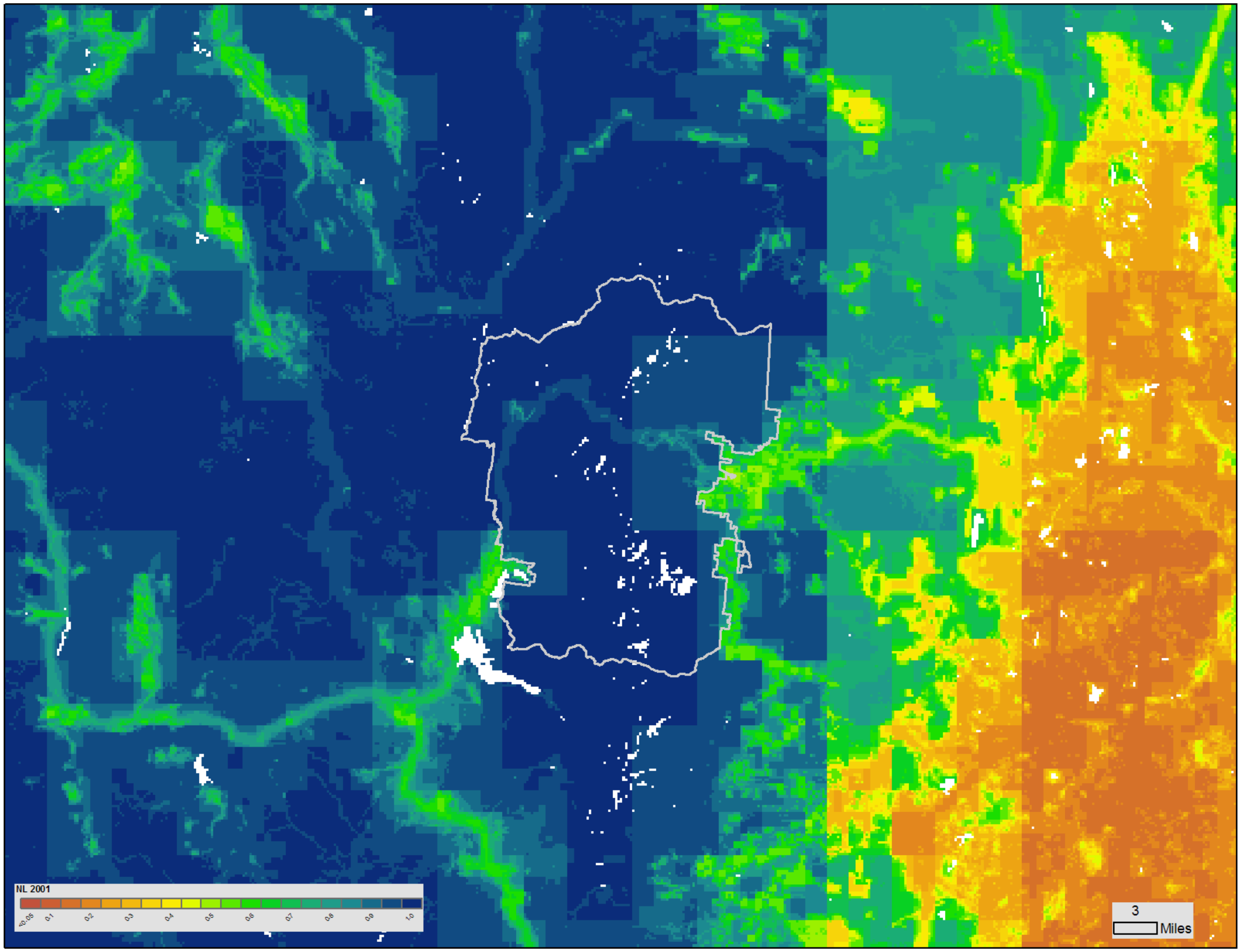


Figure 61. Natural landscapes (NL) metric values in 2030 for Rocky Mountain National Park, Colorado. The mean NL value is 0.9471 – which includes only changes due to forecasted housing density outside of the park. Natural landscapes are shown in blue, while highly-modified landscapes (low values) are shown in orange/red.

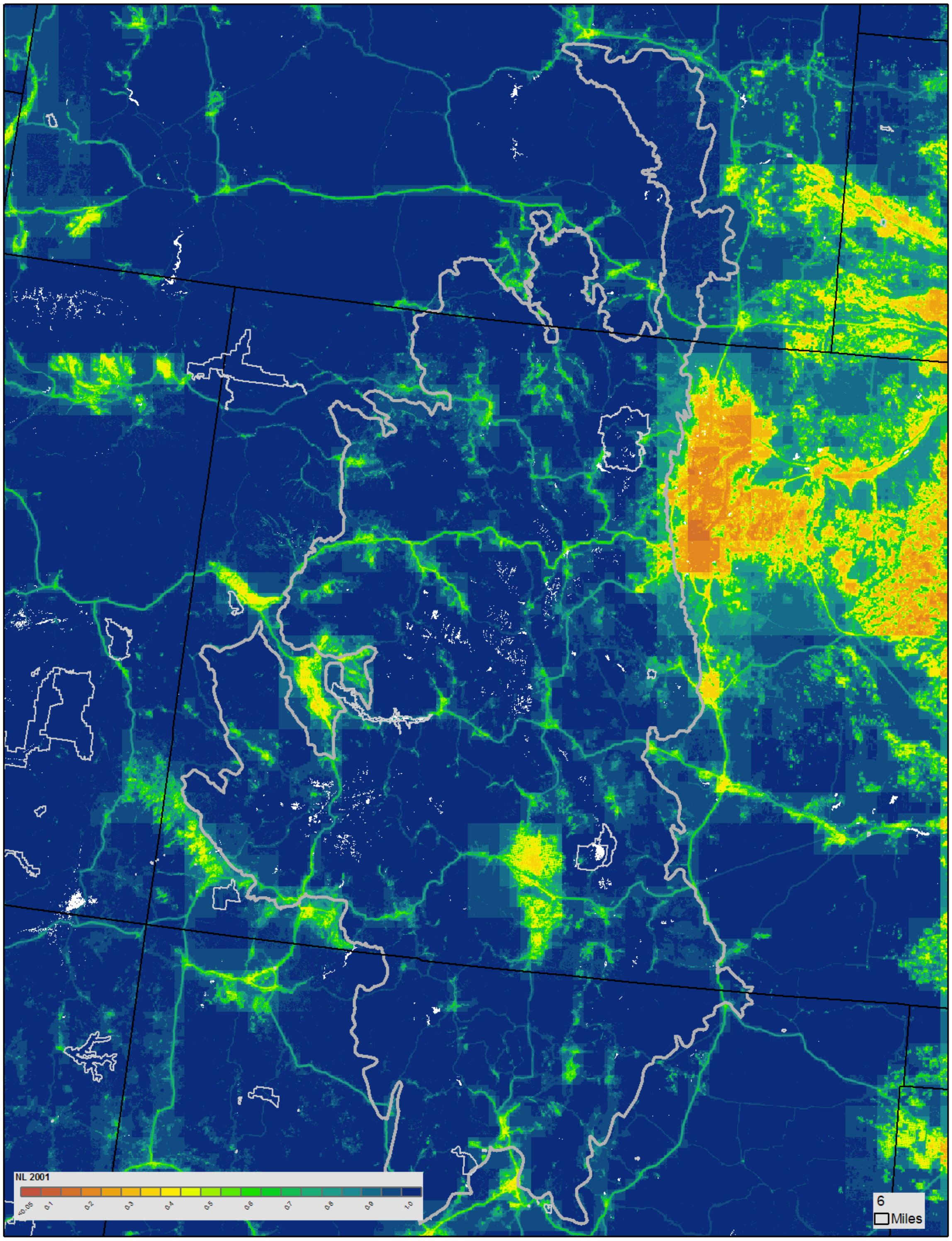


Figure 62. Natural landscapes (NL) values in 2001 for the Southern Rocky Mountain Ecoregion (boundary shown in thick grey line). Natural landscapes are shown in blue, while highly-modified landscapes (low values) are shown in orange/red.

Uses and Limitations

The results of this indicator suggest a high degree of concern, because the NL values for much of the ROMO area are among the top 10% within the Southern Rockies Ecoregion. Moreover, residential growth at the southwestern boundary of ROMO (with Granby, Frasier River corridor, etc.), more extensive land use associated with the Colorado State Forest, and widespread beetle outbreak, all combine to justify a *high degree of concern*. Overall our level of confidence in this indicator is *moderate/low*. There is *moderate agreement* among scientists that broad-scale, landscape connectivity among large patches of relatively intact habitat is critical for long-term ecological processes. However, we have relatively *low amount of evidence* to parameterize landscape connectivity models—particularly in the response of species and processes to likely fragmentation effects of roads and urban areas.

Advantages of the NL metric in evaluating the effect of humans on natural landscapes include: a simple metric that has a direct physical interpretation related to proportion of natural habitat lost at a location; includes broader, landscape-scale patterns to differentiate the spatial context; and represents landscapes as a gradient rather than binary or categorical objects (e.g., patch). Because it does not rely on patch definition nor on pre-established critical scales, NL avoids a persistent problem of the arbitrariness of defining a patch. Although the specification of neighborhoods used in computing NL was arbitrary, there is broad support in the literature (e.g., Forman et al. 2003; Hansen et al. 2005) for a distance-decay effect from localized land cover changes. Expanding or contracting the size of a neighborhood along the logarithmic progression results in relative weighting changes less than 4.7%. There are some slight artifacts in the maps (vertical and horizontal lines) that are caused by aggregating hierarchically to coarser resolution (rather than using moving windows), but the advantage to use aggregation is that overall proportions are maintained precisely with each larger neighborhood, whereas there can be some smoothing effects using moving windows.

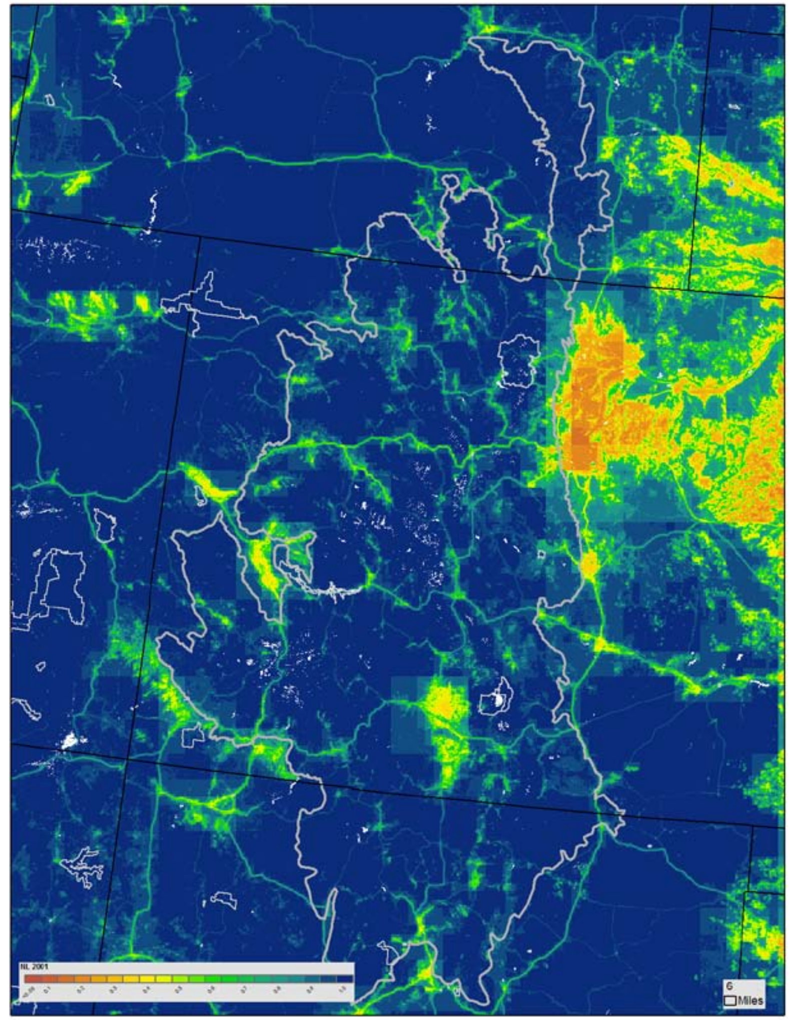
Summary: Landscapes - Connectivity of natural landscapes

What:	Measures the natural landscape context of ROMO within the Southern Rockies Ecoregion (SRE).
Why:	Movement of animals and ecological processes connect the park to adjacent landscapes beyond the park boundary.
Stressors:	Land use change, climate change
Confidence:	High degree of concern; moderate evidence, moderate agreement

Rocky Mountain National Park maintains natural landscapes that are placed within a key location to maintain connections to adjacent natural areas, especially to the north and west.

Time period	Natural Landscapes metric Reference (SRE)	Natural Landscapes metric ROMO
1992	0.931678	0.957785
2001	0.924163	0.955563
2030	0.916705	0.947110

* Data sources: NLCD retrofit product, SERGoM (Theobald 2005); National Transportation Atlas



5. Natural Resource Condition Summaries

Our goal in this section is to summarize findings about the natural resource condition of ROMO. Our approach here is explicitly *not* to provide a cumulative score that integrates across all indicators for each watershed or management unit, nor a single, overall park condition score. We do not provide an overall score both because there is a paucity of data and knowledge to make such statements for nearly all indicators, and because of challenges to combining indicators that respond in non-linear ways (Schultz 2001). Moreover, the advisory team provided guidance that the best use of this report and datasets is to provide some general indication of concern, and to provide summaries of the indicators by watershed. The ideal use of the findings of this report and the spatial datasets provided with the assessment is to inform and support park managers and scientists in developing recommendations about overall conditions in the park. We provided a general discussion and summarize each indicator by HUC-12 watershed (Table 38) as well as the raw and normalized data in a well-documented summary GIS dataset that can be used by park staff to explore further. Our intent is to help provide a decision support system that facilitates park managers and scientists to explore the spatial pattern of high and low scores that reflect different incorporation of and weighting of different indicators. We also discussed our indicators within the context of *management zones.*

Generally, lakes in east-side watersheds exhibit higher than background nitrate concentrations, lower than expected acid-neutralizing capacity, and elevated concentrations of dieldrin and DDT, while lakes in west-side watersheds exhibit harmful concentrations of mercury. We did not summarize the indicators of atmospheric deposition by watershed because they reflect a broader scale pattern.

Roughly half of the riparian and wetland areas are in the Fall River, East Inlet, Hague Creek, Colorado River West, Big Thompson River West, Cache la Poudre South, Colorado River North, and North Inlet watersheds (Figure 63; ordered highest to lowest). Of these watersheds, the Fall River, East Inlet, Hague Creek Big Thompson River West, Cache la Poudre South, and Colorado River West currently have higher than average levels of freshwater connectivity (ordered highest to lowest). Compared to other areas within the broader Southern Rockies Ecoregion, ROMO has slightly larger patches of riparian and wetlands areas.

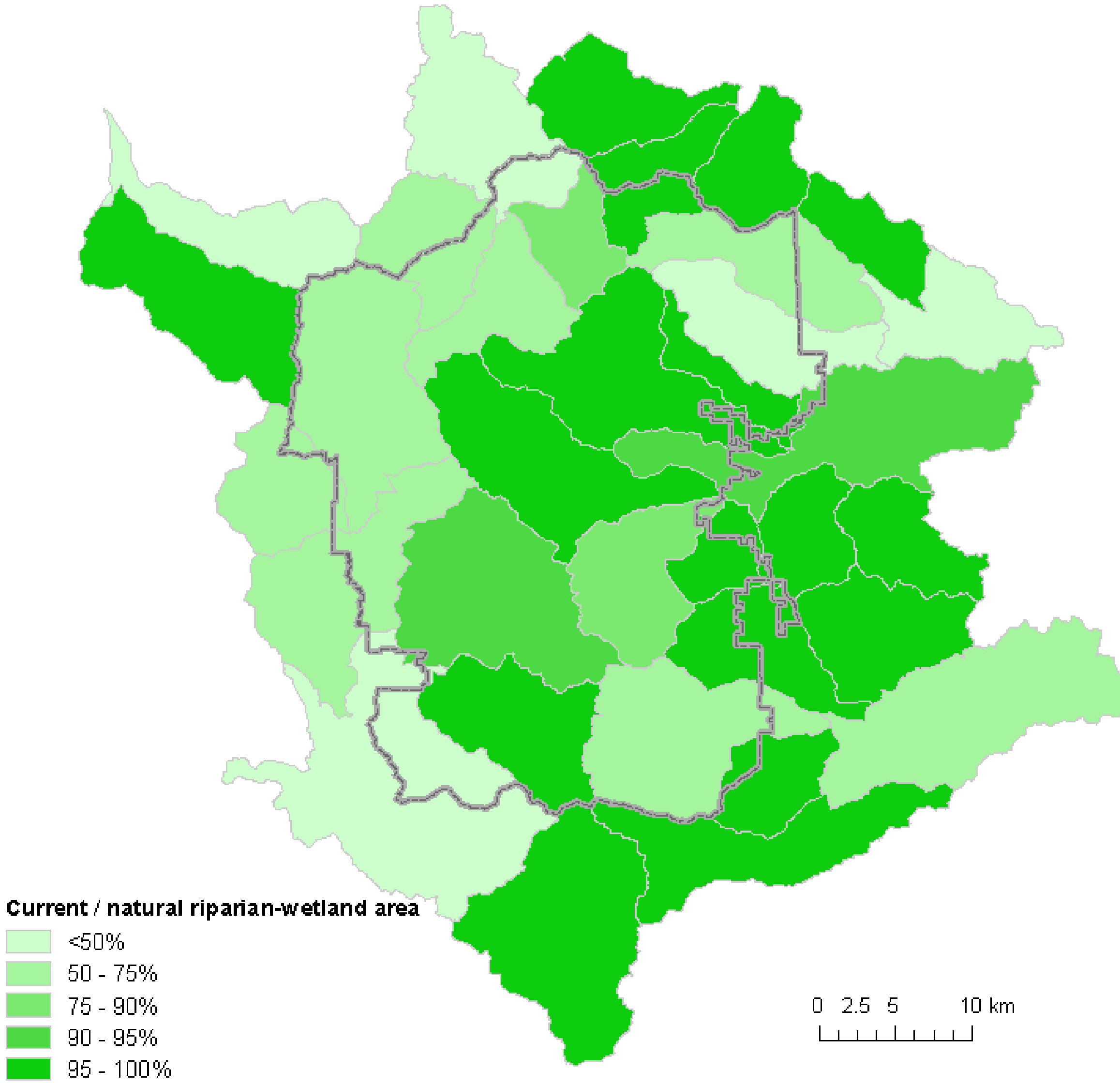


Figure 63. Watershed summary of riparian/wetland condition, calculated as the percent of connected area currently, normalized by "natural" conditions. Darker green watersheds have higher condition of riparian/wetland communities.

Watersheds that have higher than one standard deviation above average of exotic terrestrial plant species include the West Fork of the Little Thompson, the Little Thompson River, North Fork of the Big Thompson River (East), Colorado River West, and the Big Thompson River West (ordered highest to lowest). Of these, a key watershed to focus on would be the Big Thompson River West because of its high proportion of exotics and central location within the park. Watersheds with the lowest proportion of exotic species include Pennock Creek, Buchanan Creek, South Fork Michigan River, Comanche, East Inlet, La Poudre Pass Creek, Hague Creek, North Inlet, Cache la Poudre, and Michigan Rivers (ordered lowest to higher). The southern and northern watersheds have relatively low percentages of exotic species, though the southern watersheds (East and North Inlets) should be monitored closely because of their adjacency with areas of high exotic species (Colorado River West, Big Thompson River West). The key watersheds in terms of beaver restoration potential include the Big Thompson River West, Colorado River North, and Onahu Creek watersheds. Historically these had relatively high densities of beaver.

The patch sizes of upper-elevation forests and riparian/wetland communities, particularly in the north and south-central watersheds (Figure 64 and Figure 65), are significantly larger than those on average in the Southern Rockies.

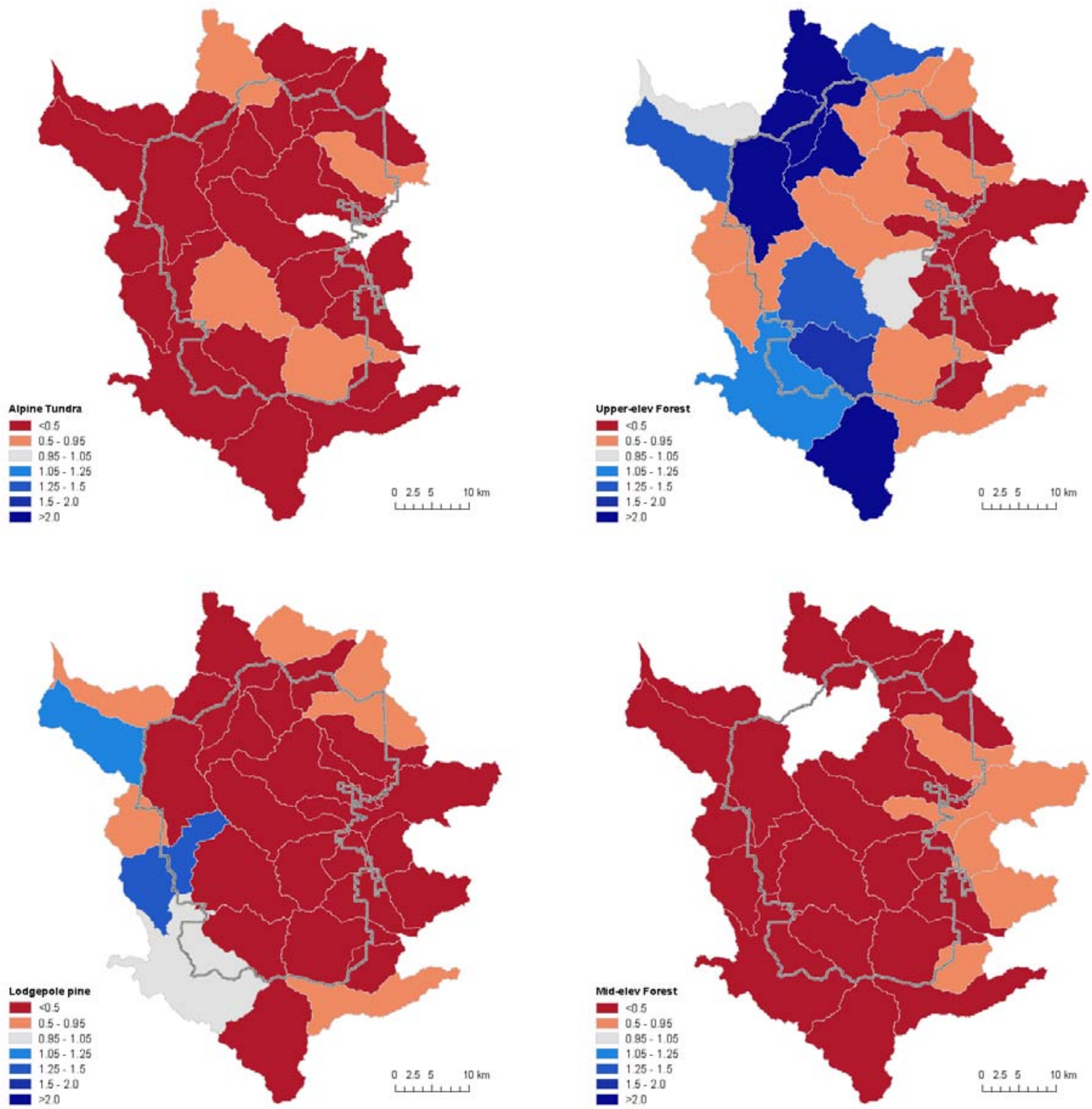


Figure 64. The ratio of patch size in ROMO to the weighted mean patch size for the Southern Rockies Ecoregion (the reference distribution), averaged within each HUC12 watershed. Areas in red show watershed condition lower than the reference distribution, while blue shows higher than reference condition.

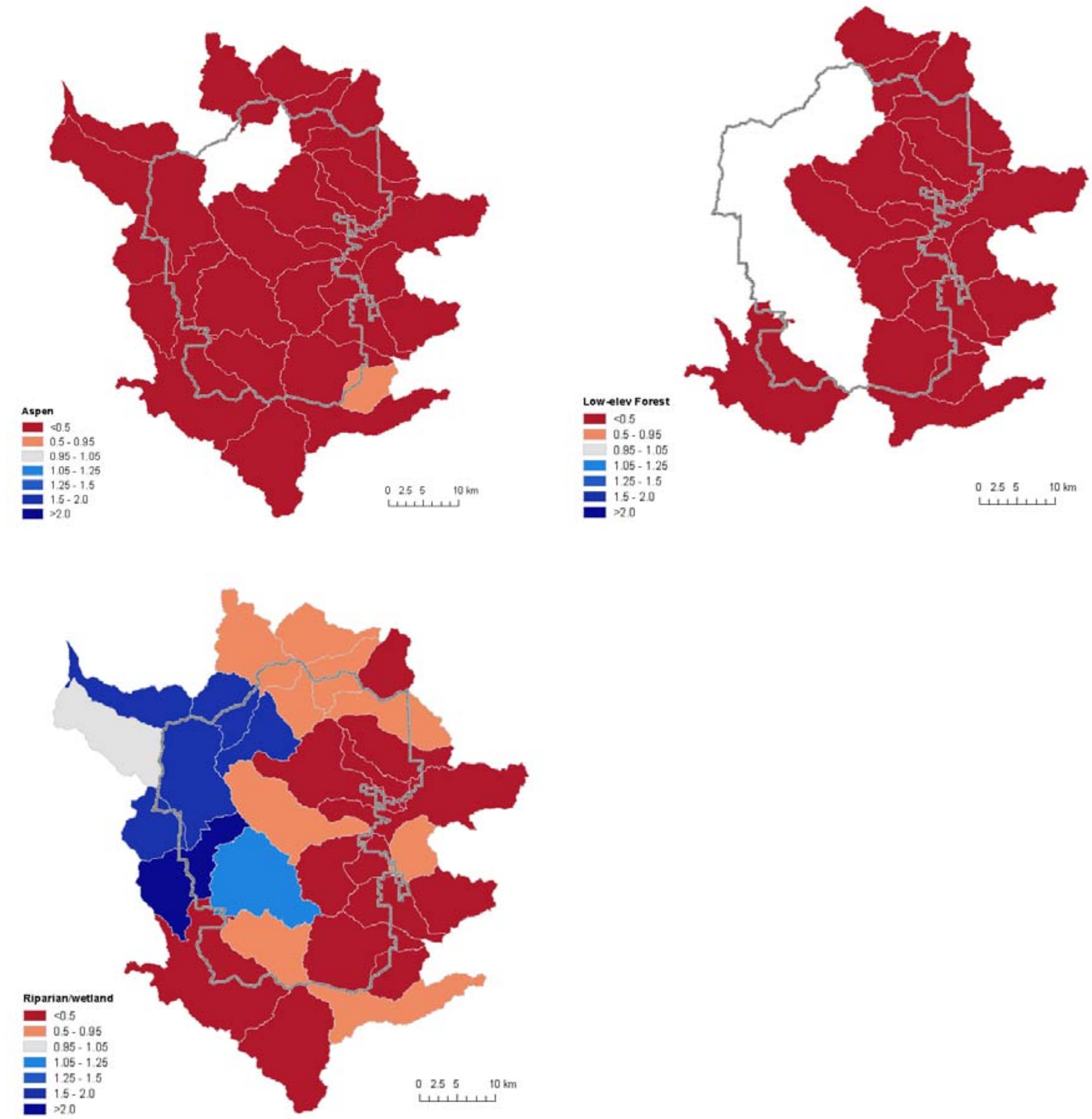


Figure 65. The ratio of patch size in ROMO to the weighted mean patch size for the Southern Rockies Ecoregion (the reference distribution), averaged within each HUC12 watershed. Areas in red show watershed condition lower than the reference distribution, while blue shows higher than reference condition.

About 7% of the park is accessible to visitors within one-hours travel time (one-way), but about 50% of the park is accessible to day use (up to four hours one-way) and 80% within eight hours. In terms of potential effects related to visitor use, Aspen Brook, Black Canyon Creek, Fall River, Cabin Creek, and the Cache la Poudre South, Onahu Creek, Glacier Creek, and Colorado River North watersheds are relatively accessible (ordered most to least accessible Table 38).

Note that we also provide the summary pages from each individual indicator below.

Table 38. A summary of indicator condition by watershed (HUC-12). Note that three condition classes (high, moderate, low) provided below are to be used for general interpretation only; they are arbitrarily assigned to the values calculated by relating the raw indicator value to its reference distribution. Summary values: P = pristine (>95% rip/wet and <2% exotic species); R = restoration opportunity (>10% suitable beaver habitat); I = issue (either <2.5 hours travel time or >20% affected by beetle).

Catchment Name (*mostly outside ROMO)	Rip/Wet % Nat	% Exotic Plants	% Beaver Habitat	Upper-elev Forest Ratio	Travel Time (hrs)	% Affected by Beetle 2008	Summary
EAST SIDE							
Aspen Brook	100.0	4.50	0.15	0.15	1.59	22.62	I
*Big Thompson River East	93.5	3.68	1.29	0.04	2.04	3.57	
Big Thompson River West	100.0	4.62	12.01	0.62	3.67	24.17	R, I
Black Canyon Creek	100.0	1.14	0.90	0.18	2.12	10.46	P, I
Cabin Creek	100.0	3.44	0.09	0.34	2.46	33.84	I
*Cache la Poudre North	35.4	0.31	1.87	2.18	6.26	12.91	
Cache la Poudre South	55.7	0.18	10.55	2.00	2.53	46.60	R, I
Comanche	100.0	0.00	0.00	1.44	8.30	0.00	P
Cow Creek	48.5	3.13	0.52	0.52	3.60	8.57	
Fall River	97.8	3.64	7.22	0.57	2.39	25.74	I
*Fish Creek	100.0	3.29	0.61	0.12	2.14	4.99	
Glacier Creek	76.7	3.10	3.30	0.95	2.98	15.46	
Hague Creek	89.4	0.15	4.88	0.91	5.90	25.01	I
La Poudre Pass Creek	57.7	0.11	2.99	2.06	5.54	30.55	I
*Little Thompson River	100.0	8.41	0.00	0.02	2.84	5.15	
Michigan River	11.0	0.28	0.00	0.99	7.44	0.00	
Middle Saint Vrain Creek	100.0	1.67	0.00	0.52	4.28	11.49	P
*Miller Fork	100.0	2.60	0.00	0.00	3.71	4.95	
North Fork Big Thompson (East)	25.9	7.98	0.00	0.00	2.58	0.93	I
North Fork Big Thompson (West)	52.7	0.83	0.38	0.44	3.93	6.04	
North Saint Vrain Creek (East)	67.8	0.74	6.93	0.89	4.13	24.93	
*North Saint Vrain Creek (West)	62.6	0.95	0.00	0.00	3.20	2.48	
*Pennock Creek	100.0	0.00	0.00	0.69	5.49	4.90	
*Rock Creek	100.0	2.75	0.00	0.44	2.84	41.71	
South Fork Cache la Poudre	100.0	1.25	1.65	0.68	7.30	11.65	P
*South Fork Michigan River	100.0	0.00	0.00	1.36	6.38	0.00	
*West Fork Little Thompson River	100.0	9.00	0.00	0.00	2.30	0.57	
WEST SIDE							
*Bowen	50.4	4.15	7.81	0.62	2.96	10.36	
Buchanan Creek	100.0	0.00	0.00	2.78	9.94	0.00	P
Colorado River North	56.3	0.92	12.37	2.68	3.00	23.19	R, I
*Colorado River West	44.3	5.36	0.30	1.21	8.40	10.58	
East Inlet	100.0	0.07	2.70	1.76	5.74	12.75	P
North Inlet	91.2	0.16	3.64	1.36	4.51	18.00	
Onahu Creek	51.6	3.28	17.83	0.56	2.64	19.03	R
CONDITION/ISSUE (absence)							
High	90.0	2.00	5.00	1.10	5.00	10.00	
Moderate	80.0	5.00	2.00	0.90	2.50	25.00	
Low	50.0	10.00	0.00	0.00	0.00	50.00	

Table 39. Summary of raw indicator values by management zones outlined in the ROMO Backcountry Wilderness Management Plan (BWMP).

Indicator	Sub-indicator measure	Management zones					
		RNAs	Alpine Tundra	Cross Country	Corridors	Front Country	Not covered in BWMP
Air & climate	Condition of alpine lakes	Deposition closer to pristine	Deposition impacted; climate at risk	-	-	-	-
	Atmospheric deposition	Elevated on east side	Elevated on east side	-	-	Elevated on east side	-
Water	Wetland/riparian areas	7.5%	3%	2%	5.5%	2.5%	0.1%
Biotic integrity	Exotic terrestrial (average % exotic by zone)	0.15%	0.04%	6.2%	3.0%	22.5	35.6%
	Non-native fish (% of streams)	22%	0.08%	13%	16.6%	13.4%	4%
	Potentially suitable beaver habitat (% of zone in habitat)	3%	14%	2%	14%	14%	6%
Landscapes	Ecological systems (% of zone by system) Alpine Lower Montane Open Water Riparian/Wetland Savanna Upper Montane	 39.0 2.8 1.5 9.1 0.8 46.8	-	 42.0 1.3 0.06 6.3 0.001 50.3	 19.5 3.7 1.3 14.8 1.7 59.0	 1.3 22.0 1.2 9.5 14.4 51.6	 3.1 10.8 1.1 22.6 11.2 51.2

Discussion

Each indicator described in this report represents only one method for evaluating the rich and diverse resources in Rocky Mountain National Park. To conclude with a simple and single assessment of the condition of the park as a whole is a complex and complicated task, and one that may have very little meaning either to managers or other stakeholders. The approach presented here provides a diversity of indicators—based on the best data and science available—that, when used together, can provide an overall sense of what is occurring in different locations and by different measures (Table 40). Through exploring the relevant datasets from each indicator and overlaying them with each other, patterns may be observed, additional questions will arise, and new strategies for management may evolve.

Table 40. Main findings of the watershed condition assessment.

Level 1	Indicator	Reference distribution	Concern	Summary
Air & Climate	Condition of alpine lakes and atmospheric deposition	Interpretation of historical condition and ambient distributions to identify Minimally Disturbed Condition	High degree of concern; moderate evidence, high agreement	East-side lakes have higher than background nitrate concentrations and lower than expected acid-neutralizing capacity (ANC) and concentrations of dieldrin & DDT are also elevated, while west-side mercury in fish tissue is at or above concentrations that are harmful for some birds and mammals. West-side nitrate and ANC are consistent with reference conditions, and lake pH and chemical concentrations of calcium, chloride, sulfate, ammonium for all ROMO lakes are consistent with reference conditions
Water	Extent and connectivity of wetland and riparian areas	Interpretation of historical condition to identify Minimally Disturbed Condition	High degree of concern; low evidence, moderate agreement.	Restoration of four dams and four ditches has improved the connectivity of riparian and wetland communities somewhat from 1900-1990s conditions, but current conditions (shown right) remain substantially fragmented compared to “natural” hydrological conditions.
Biotic Integrity	Extent of exotic terrestrial plants	Interpretation of historical condition to identify Minimally Disturbed Condition	High degree of concern; moderate evidence, moderate agreement.	The distribution of known locations of exotic plants (especially cheatgrass) is strongly correlated with accessibility, with roughly 80% of known locations in highly accessible areas (<1 hour). East-side watersheds have higher rates of invasive species (2.8% vs. 1.8%), and lower montane and riparian ecological systems are particularly affected.

Level 1	Indicator	Reference distribution	Concern	Summary
	Left blank on purpose			
	Extent of fish distributions	Interpretation of historical condition to identify Minimally Disturbed Condition	High degree of concern; low evidence, moderate agreement.	Currently the proportion of streams that are “secure” (native only or fishless above a barrier) is 10% and there are 54 known human barriers, and native-only streams have increased slightly from 7.0% to 7.3% in the past 50 years.
	Extent of suitable beaver habitat	Best professional judgment to identify Minimally Disturbed Condition	High degree of concern; moderate evidence, moderate agreement.	The current distribution of beaver is far below historic levels. Highest areas for restoration potential (right map) include Colorado River (north); Big Thompson River (west), Onahu Creek, Cache la Poudre (south), Fall River, and Glacier Creek watersheds.
Land-scapes	Extent and pattern of major ecological systems	Best professional judgment to identify Ambient Distribution	Low degree of concern; low evidence, moderate agreement.	Generally the extent and pattern of ecological systems within the park are similar to those found within the broader Southern Rockies Ecoregion, although there was some indication that there were more large patches of high montane forest and riparian/wetland
	Natural landscapes and connectivity	Best professional judgment and Ambient Distribution	High degree of concern; moderate evidence, moderate agreement.	How are ranges in habitat and Rocky Mountain National Park maintains natural landscapes that are placed within a key location to maintain connections to adjacent natural areas, especially to the north and west.

Data and Knowledge Gaps

Major data gaps in this assessment include data on hydrologic variability–both surface and ground water flows–as there are only three stream gages in the park with a decent historical record. Fine-grained vegetation data outside of the park that is comparable to the ROMO vegetation would also be quite useful to better understand the extent and pattern of major ecosystem types (rather than relying on relatively coarse 30 m satellite imagery-based data, i.e., LANDFIRE). There also were suggestions to better integrate this analysis with the Facility Management (FMSS) database.

Appendix 1. Literature Cited

Alexander, S., Waters, N., & Paquet, P. (2005). Traffic volume and highway permeability for a mammalian community in the Canadian Rocky Mountains. *The Canadian Geographer*, 49 (4):321-331.

Aplet, G., J. Thomson, and M. Wilbert. (2000). Indicators of wildness: using attributes of the land to assess the context of wilderness. In: McCool, S.F., D.N. Cole, W.T. Borrie, J. O'Loughlin. 2000. Wilderness science in a time of change conference—Volume 2: Wilderness within the context of larger systems; 1999 May 23–27; Missoula, MT. Proceedings RMRS-P-15-VOL-2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 89-98.

Bailey, R.G. (1995). *Descriptions of Ecoregions of the United States*. U.S. Forest Service Miscellaneous Publication Number 1391, Washington, D.C., USDA Forest Service.

Baker, B. (2003). Beaver (*Castor canadensis*) in heavily browsed environments. *Lutra*, 46:173-181.

Baker, B. (2005). Efficacy of tail-mounted transmitters for beaver. *Wildlife Society Bulletin*, 34: 218-222.

Baker, B. et al. (2005). Interaction of beaver and elk herbivory reduces standing crop of willow. *Ecological Applications*, 15:110-118.

Baker, B., & Hill, E. (2003). Beaver (*Castor canadensis*). In G. Fledhamer, B. Thompson, & J. Chapman, Wild mammals of North America: biology, management, and conservation. 2nd edition. (pp. 288-310). Baltimore, Maryland: The Johns Hopkins University Press.

Baker, B., Peinetti, H., & Coughenour, M. (2005). Resilience of willow stems after release from intense elk browsing. *Rangeland Ecology and Management*, 58:575-581.

Baker, W. (2000). Measuring and analyzing forest fragmentation in the Rocky Mountains and western United States. In R. Knight, F. Smith, S. Buskirk, W. Romme, & W. Baker, Forest Fragmentation in the Southern Rocky Mountains (pp. 55-94). Boulder, CO: University Press of Colorado.

Barber, M. (1994). Environmental Monitoring and Assessment Program Indicator Development Strategy. U.S. Environmental Protection Agency. Athens, GA: U.S. Environmental Protection Agency.

Barnes, D., & Mallik, A. (1997). Habitat factors influencing beaver dam establishment in a Northern Ontario watershed. *The Journal of Wildlife Management*, 61:1371-1377.

Baron, J. (2004). Research in National Parks.Introduction to Forum on same topic. Ecological Applications, 14:3-4.

Baron, J., Norton, S.A., Beeson, D.R. and Herrmann, R. (1986). Sediment diatom and metal stratigraphy from Rocky Mountain lakes with special reference to atmospheric deposition. Canadian Journal of Fisheries and Aquatic Science. 43:1350-1362.

Baron, J., Poff, N., Angermeier, P., Dahm, C., Gleick, P., Hairston, J. N., et al. (2002). Balancing human and ecological needs for freshwater: the case for equity. Ecological Applications, 12:1247-1260.

Baron, J., Rueth, H., Wolfe, A., Nydick, K., Allstott, E., Minear, J., Moraska, B. (2000). Ecosystem responses to nitrogen deposition in the Colorado Front Range. Ecosystems, 3:352-368.

Baron, J. S., T. M. Schmidt, and M. D. Hartman. (2009). Climate-induced changes in high elevation stream nitrate dynamics. Global Change Biology 15:1777-1789.

Beier, P. (2007). Cougars, connectivity, and missing linkages: two decades of expanding vision and partnership. Transactions of the Western Section of the Wildlife Society, 43:1-7.

Beier, P., & Barrett, R. (1987). Beaver habitat use and impact in Truckee River Basin, California. Journal of Wildlife Management, 51:794-799.

Beier, P., Majka, D., & Spencer, W. (2008). Forks in the road: choices in procedures for designing wildland linkages. Conservation Biology, 22 (4):836-851.

Bergström, A.-K., P. Blomqvist, and M. Jansson. (2005). Effects of Atmospheric Nitrogen Deposition on Nutrient Limitation and Phytoplankton Biomass in Unproductive Swedish Lakes. Limnology and Oceanography 50:987-994.

Bergström, A., and M. Jansson. (2006). Atmospheric nitrogen deposition has caused nitrogen enrichment and eutrophication of lakes in the northern hemisphere. Global Change Biology 12:635-643.

Blais, J., Schindler, D., Muir, D., Kimpe, L., Donald, D., & Rosenberg, B. (1998). Accumulation of persistent organochlorine compounds in mountains of western Canada. Nature, 395: 585-588.

Bosworth, D. (2004). Four threats to the Nation's forest and grasslands. Boise, Idaho: Idaho Environmental Forum.

Botequilha Leitao, A., Miller, J., Ahern, J., & McGarigal, K. (2006). Measuring Landscapes: A Planner's Handbook. Washington, D.C.: Island Press.

Britten, M., Schweiger, E. W., Frakes, B., Manier, D., and Pillmore, D. (2007). Rocky Mountain Network Vital Signs Monitoring Plan. Natural Resource Report NPS/ROMN/ NRR-2007/010. National Park Service, Fort Collins, Colorado.

Brown, M.T. and M.J. Vivas. (2005). Landscape development intensity index. *Environmental Monitoring and Assessment* 101: 289-309.

Brown, D., Johnson, K., Loveland, T., & Theobald, D. (2005). Rural land-use trends in the conterminous United States, 1950-2000. Ecological Applications, 15 (6):1851-1863.

Burns, D. A. (2004). The effects of atmospheric nitrogen deposition in the Rocky Mountains of Colorado and southern Wyoming, USA: a critical review. Environmental Pollution 127.

Carver, S., Evans, A. and Fritz, S. (2002) Wilderness attribute mapping in the United Kingdom. *International Journal of Wilderness*. 8(1): 24-29.

Charles, D. (1991). Acid deposition and aquatic ecosystems: regional case studies. New York: Springer-Verlag.

Chetkiewicz, C., St. Clair, C., & Boyce, M. (2006). Corridors for conservation: integrating pattern and process. Annual review of Ecology, Evolution, and Systematics, 37:317-342.

Chong, G.W., R.M. Reich, M.A. Kalkhan, and T.J. Stohlgren. (2001). New approaches for sampling and modeling native and exotic plant species richness. Western North American Naturalist 61:328-335.

Chruszcz, B., Clevenger, A., Gunson, K., & Gibeau, M. (2003). Relationships among grizzly bears, highways, and habitat in the Banff-Bow Valley, Alberta, Canada. Canadian Journal of Zoology, 81 (8):1378-1391.

Cole et al. (2008). Naturalness and beyond: protected area stewardship in an era of global environmental Change. The George Wright Forum, 25(1):36-56.

Cooper, D.J., L.H. MacDonald, S.K. Wenger, and S.W. Woods. (1998). Hydrologic restoration of a fen in Rocky Mountain National Park, Colorado, USA. *Wetlands* 18(3): 335-345.

Crooks, K., & Sanjayan, M. (2006). *Connectivity Conservation.* New York: Cambridge University Press.

Dale, V., Brown, S., Haeuber, R., Hobbs, N., Huntly, N., Naiman, R., et al. (2000).Ecological principles and guidelines for managing theuse of land. Ecological Applications, 10 (3): 639-670.

Davies, S.P. and S.K. Jackson. (2006). The biological condition gradient: a descriptive model for interpreting change in aquatic ecosystems. Ecological Applications, 16(4): 1251-1266.

Davis, F., Stoms, D., Costello, C., Machado, E., Metz, J., Gerrard, R., et al. (2003). A framework for setting land conservation priorities using multi-criteria scoring and an optiman fund allocation strategy.

DeStefano, S., Koenen, K., Henner, C., & Strules, J. (2006). Transition to independence by subadult beavers (*Castor canadensis*) in an unexploited, exponentially growing population. Journal of Zoology, 269:434-441.

Dickson, B., Jenness, J., & Beier, P. (2005). Influence of vegetation, topography, and roads on cougar movement in southern California. Journal of Wildlife Management, 69 (1):264-276.

Elser, J. J., M. Kyle, L. Steger, K. R. Nydick, and J. S. Baron. (2009). Nutrient availability and phytoplankton nutrient limitation across a gradient of atmospheric nitrogen deposition. Ecology 90:3062-3073.

Elser, J. J., T. Andersen, J. S. Baron, A.-K. Bergstrom, M. Jansson, M. Kyle, K. R. Nydick, L. Steger, and D. O. Hessen. (2009). Shifts in Lake N:P Stoichiometry and Nutrient Limitation Driven by Atmospheric Nitrogen Deposition. Science 326:835-837.

Enders, S., Pagani, M., Pantoja, S., Baron, J., Wolfe, A., Pedentchouk, N., et al. (2008). Compound-specific stable isotopes of organic compounds from lake sediments track recent environmental changes in an alpine ecosystem, Rocky Mountain National Park (United States of America). Limnology and Oceanography, 53 (4):1468-1478.

ESRI. (n.d.). ArcGIS Version 9.2. Windows 2000/XP Server Operating System. Build 800. Redlands, CA.

Environmental Systems Research Institute (ESRI). 2007. GDT Streetmap 2006 database.

Fancy, S.G., J.E. Gross, and S.L. Carter. (2009). Monitoring the condition of natural resources in U.S. National Parks. *Environmental Monitoring and Assessment*, 151(1):161-174.

Fausch, K.D., Rieman, B.E., Dunham, J.B., Young, M.K., Peterson, D.P. (2009). Invasion versus isolation: Trade-offs in managing native salmonids with barriers to upstream movement. *Conservation Biology*, 23(4):859-870.

Federal Guide for Watershed Analysis (1995). Ecosystem analysis at the watershed scale. Regional Ecosystem Office, Portland, Oregon.

Fitzgerald, W., Engstrom, D., Mason, R., & Nater, E. (1998).The case for atmospheric mercury contamination in remote areas. *Environmental Science and Technology*, 32:1-7.

Foley, J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, and S.R. Carpenter. (2005). Global consequences of land use. *Science* 309:570–574. doi:10.1126/science.1111772

Forman, R.T.T., and L. E. Alexander. (1998). Roads and their major ecological effects. *Annual Review of Ecology and Systematics* 29:207-231.

Forman, R. (2003). Road ecology: science and solutions. Washington, D.C.: Island Press.

Forman, R.T.T., D. Sperling, J.A. Bissonette, A.P. Clevenger, C.D. Cutshall, V.H. Dale, L. Fahrig, R. France, C.R. Goldman, K. Heanue, J.A. Jones, F.J. Swanson, T. Turrentine, and T.C. Winter. (2003). *Road ecology: science and solutions*. Island Press, Washington, D.C.

Fortin, M.J., R.J. Olson, S. Ferson. (2000). Issues related to the detection of boundaries. *Landscape Ecology* 15:453–466

Frakes, B., Hurst, C., Pillmore, D., Schweiger, B., & Talbert, C. (2007). Travel time cost surface model, v. 20070514. Fort Collins, CO: Rocky Mountain Network, National Park Service.

Fry, J.A., Coan, M.J., Homer, C.G., Meyer, D.K., and Wickham, J.D. (2009) *Completion of the National Land Cover Database (NLCD) 1992–2001 Land Cover Change Retrofit product.* U.S. Geological Survey Open-File Report 2008–1379, 18 p.

Gardner, R.H., B.T. Milne, M.G. Turner, and R.V. O'Neill. (1987). Neutral models for the analysis of broad-scale landscape pattern. *Landscape Ecology* 1:19–28.

Gardner, R.H. and D.L. Urban (2007). Neutral models for testing landscape hypotheses. *Landscape Ecology* 22(1):15-29.

Gaucherel, C. (2007). Multiscale heterogeneity map and associated scaling profile for landscape analysis. *Landscape and Urban Planning* 82: 95-102.

Garrels, R.M. and Mackenzie, F.T. (1967). Origin of the chemical compositions of some springs and lakes: equilibrium concepts in natural water systems. American Chemical Society Adv. Chem. Ser.67:222–242.

Geertman, S.C.M., and J.R. Ritsema van Eck. (1995). GIS and models of accessibility potential: anapplication in planning. *International Journal of Geographical Information Systems* 9(1): 67-80.

Gibson, J. H., J. N. Galloway, C. Schofield, W. McFee, R. Johnson, S. McCarley, N. Dise, and D. Herzog. (1983). Rocky Mountain acidification study. FWS/OBS-80/40.17.

Gillison, A.N. and K.R.W. Brewer. (1985). The use of gradient directed transects or gradsects in natural resource survey. Journal of Environmental Management. 20:103-127.

Gilpin, M. E., and M. E. Soulé. (1986). Minimum viable populations:processes of speciesextinction. Pages 19-34 *in* M. E. Soulé, editor.Conservation biology: the science of scarcity and diversity.Sinauer Associates, Sunderland, Massachusetts.

Girvetz, E.H., J.H. Thorne, A.M. Berry, and J.A.G. Jaeger. (2008). Integration of landscape fragmentation analysis into regional planning: A statewide multi-scale case study from California, USA. *Landscape and Urban Planning* 86: 205-218.

Gonzalez-Abraham, C. E., V.C. Radeloff, R. B. Hammer, T. J. Hawbaker, S. I. Stewart, M. K. Clayton. (2007). Patterns of houses and habitat loss from 1937 to 1999 in northern Wisconsin, USA. *Ecological Applications* 17(7): 2011-2023.

Groffman, P.M., J.S. Baron, T. Blett, A.J. Gold, I. Goodman, L.H. Gunderson, B.M. Levinson, M.A. Palmer, H.W. Paerl, G.D. Peterson, N.L. Poff, D.W. Rajeski, J.F. Reynolds, M.G. Turner, K.C. Weathers, J. Wiens (2006). Ecological thresholds: the key to successful environmental management, or an important concept with no practical application? Ecosystems, 9:1-13.

Gross, J. (2003). Developing conceptual models for monitoring programs. NPS Inventory and Monitoring Program.

Gross, J.E., S.J. Goetz, and J. Cihlar. (2009). Application of remote sensing to parks and protected area monitoring: Introduction to the special issue. *Remote Sensing of Environment* 113: 1343-1345.

Gustafson, E.J. (1998) Quantifying landscape spatial pattern: What is the state of the art? *Ecosystems* 1: 143-156.

Hajkowicz, S. (2006). Multi-attributed environmental index construction. Ecological Economics, 57: 122-139.

Hannah, L., J.L. Carr, and A. Lankerani. (1995). Human disturbance and natural habitat: a biome level analysis of a global data set. *Biodiversity and Conservation* 4: 128-155.

Hansen, A., & Brown, D. (2005). Land-use change in rural America: Rates, drivers, and consequences. *Ecological Applications*, 15 (6):1849-1850.

Hansen, A., & DeFries, R. (2007). Ecological mechanisms linking protected areas to surrounding lands. Ecological Applications, 17:974-988.

Hansen, A., Knight, R., Marzluff, J., Powell, S., Brown, K., & Gude, P. J. (2005). Effects of exurban development on biodiversity: Patterns, mechanisms, and research needs. Ecological Applications, 15 (6):1893-1905.

Hargis, C., Bissonette, J., & David, J. (1998). The behavior of landscape metrics commonly used in the study of habitat fragmentation. Landscape Ecology, 13:167-186.

Hartman, M. D., J. S. Baron, and D. S. Ojima. (2007). Application of a coupled ecosystem-chemical equilibrium model, DayCent-Chem, to stream and soil chemistry in a Rocky Mountain watershed. Ecological Modelling200:493-510.

Harwell M. A., Myers V, Young T, Bartuska A,Gassman N, et al. (1999). A framework for anecosystem integrity report card. *BioScience*49:543–56.

Hauer, F.R. and R.D Smith. (1998). The hydrogeomorphic approach to functional assessment of riparian wetlands: evaluating impacts and mitigation on river floodplains in the USA. Freshwater Biology, 40: 517-530.

Heemskerk, M., K. Wilson, and M. Pavao-Zuckerman. (2003). Conceptual models as tools for communication across disciplines. Conservation Ecology **7**(3): 8. [online] URL: http://www.consecol.org/vol7/iss3/art8/

Heinz Center. (2008). *The State of the Nation's Ecosystems 2008: Measuring the Land, Waters, and Living Resources of the United States*. Island Press. Washington, DC.

Higgins, J.V., Bryer, M.T., Khoury, M.L., Fitzhugh, T.W. (2005) A Freshwater Classification Approach for Biodiversity Conservation Planning. *Conservation Biology*, 19 (2): 432-445.

Hilderbrand, R. H., and J. L. Kershner. (2000). Conserving inland cutthroat trout in small streams:how much streamis enough? *North American Journal of Fisheries Management* 20:513–520.

Hill, E. (1982).Beaver (*Castor canadensis*). In J. Chapman, & G. Feldhamer, *Wild mammals of North America* (pp. 256-281). Baltimore, Maryland: The Johns Hopkins University Press.

Hilty, J., Lidicker, W., & Merenlender, A. (2006). *Corridor ecology: The science and practice of linking landscapes for biodiversity conservation.* Washington, D.C.: Island Press.

Irwin, E. G., N. E. Bockstael. (2007). The evolution of urban sprawl: Evidence of spatial heterogeneity and increasing land fragmentation. Proceedings of the National Academy of Sciences of the United States of America 104(52)**:**20672-20677.

Jaeger, J.A.G., J. Bowman, J. Brennan, L. Fahrig, D. Bert, J. Bouchard, N. Charbonneau, K. Frank, B. Gruber, and K.T. von Toschanowitz. (2005). Predicting when animal populations are at risk from roads: an interactive model of road avoidance behavior. *Ecological Modelling* 185: 329-348.

Jensen, M.E., I.A. Goodman, P.S. Bourgeron, N.L. Poff, and C.K. Brewer. (2001). Effectiveness of biophysical criteria in the hierarchical classification of drainage basins. Journal of the American Water Resources Association, 37: 1155-1167.

Johnson, P.T.J., Olden, J.D., and Vander Zanden, M.J. (2008). Dam invaders: impoundments facilitate biological invasions in freshwaters. Frontiers in Ecology and the Environment 6: 357-363.

Jones, K. B., Riitters, K. H., Wickham, J. D., Tankersley, R. D., Jr., O'Neill, R. V., Chaloud, D. J.; Smith, E. R.; Neale, A. C. (1997). An Ecological Assessment of the United States Mid-Atlantic Region: A Landscape Atlas. United States Environmental Protection Agency. Office of Research and Development, Washington DC, 20460. EPA/600/R-97/130.

Jones, K. B., A. C. Neale, T. G. Wade, J. D. Wickham, C. L. Cross, C. M. Edmonds, C.M. T. R. Loveland, M. S. Nash, K. H. Riitters, and E. R. Smith. (2001). The consequences of landscape change on ecological resources: an assessment of the United States Mid-Atlantic Region, 1973-1993. *Ecosystem Health* 7:229-242.

Kalkhan, M.A., E.J. Stafford, P.J. Woodly, and T.J. Stohlgren. (2006). Assessing exotic plant species invasions and associated soil characteristics: a case study in eastern Rocky

Mountain National Park, Colorado, USA, using the pixel nested plot design. *Applied Soil Ecology* 35(3): 622-634.

Kalkhan, M.A., E.J. Stafford, and T.J. Stohlgren. (2007). Rapid plant diversity assessment using a pixel nested plot design: A case study in Beaver Meadows, Rocky Mountain National Park, Colorado, USA. Diversity and Distributions 13(4): 379-388.

Kindlmann, P., & Burel, F. (2008). Connectivity measures: a review. *Landscape Ecology*, 23: 879-890.

Kliskey, A.D. (1998). Linking the wilderness perception mapping concept to the Recreation Opportunity Spectrum. *Environmental Management* 22(1): 79-88.

Knapp, R., Corn, P., & Schindler, D. (2001). The introduction of nonnative fish into wilderness lakes: good intentions, conflicting mandates, and unintended consequences. *Ecosystems*, 2:275-278.

Knapp, R., Matthews, K., & Sarnell, O. (2001). Resistance and resilience of alpine lake faunal assemblages to fish introductions. *Ecological Monographs*, 71:401-421.

Knight, D.H, & Reiners, W.A. (2000).Natural patterns in the southern Rocky Mountain landscapes and their relevance to forest management. In R. Knight, F. Smith, S. Buskirk, W. Romme, & W. Baker, Forest Fragmentation in the Southern Rocky Mountains (pp. 15-30). Boulder, CO: University Press of Colorado.

Kupfer, J.A., G.P. Malanson, and S.B. Franklin. (2006). Not seeing the ocean for the islands: the mediating influence of matrix-based processes on forest fragmentation effects. *Global Ecology and Biogeography* 15: 8-20.

Lafreniere, M., & Sharp, M. (2005). A comparison of solute fluxes and sources from glacial and non-glacial catchments over contrasting melt seasons. Hydrologic Processes, 19:2991-3012.

Landers, D. H., J. M. Eilers, D. F. Brakke, W. S. Overton, P. E. Kellar, W. E. Silverstein, R. D. Schonbrod, R. E. Crowe, R. A. Linthurst, J. M. Omernik, S. A. Teague, and E. P. Meier. (1987). Characteristics of Lakes in the Western United States - Volume I: Population Descriptions and Physico-Chemical Relationships. U.S. Environmental Protection Agency, Washington DC.

Landers, D. H.; Simonich, S. L.; Jaffe, D. A.; Geiser, L.; Campbell, D. H.; Schwindt, A.; Schreck, C.; Kent, M.; Hafner, W. D.; Taylor, G. E.; Hageman, K. J.; Blett, T.; Erway, M. M.; Pierson, S.; Christie, S. *An Assessment of Airborne Contaminants in National Parks of the Western United States*; EPA/600/R-03/035; U.S. Environmental Protection Agency, Office of Research and Development, NHEERL, Western Ecology Division: Corvallis, OR, 2007. http://www2.nature.nps.gov/air/Studies/air_toxics/wacap.cfm. (2007). Landres, P., Morgan, P., & Swanson, F. (1999). Overview of the use of natural variability concepts in managing ecological systems. Ecological Applications, 9:1179-1188.

Leibowitz, S., Cushman, S., & Hyman, J. (1999). Use of scale invariance in evaluating judgment indicators. Environmental Monitoring and Assessment, 58:283-303.

Leinwand, I. (2009). *Land use patterns and trends in the Southern Rocky Mountains, U.S. at the public-private interface*. MS Thesis, Colorado State University.

Lesslie, R.G., B.G. Mackey, and K.M. Preece. (1988). A computer-based method of wilderness evaluation. *Environmental Conservation* 15(3):225-232.

Leu, M., S.E. Hanser, and S.T. Knick. (2008). The human footprint in the West: A large-scale analysis of anthropogenic impacts. *Ecological Applications* 18(5): 1119-1139.

Li, B., & Archer, S. (1997). Weighted mean patch size: a robust index for quantifying landscape structure. *Ecological Modelling*, 102:353-361.

McLaran, C.G. (2006). New River Gorge Natural Resource Assessment: Methodology and Critique. George Write Society. In: Harmon,David,ed.2006.People, Places, and Parks: Proceedings of the 2005 George Wright Society Conference on Parks, Protected Areas, and Cultural Sites. Hancock,Michigan: The George Wright Society.

Mattson, K.M. and P.L. Angermeier. (2007). Integrating human impacts and ecological integrity into a risk-based protocol for conservation planning. Environmental Management, 39:125-138.

McGarigal, K., Cushman, S., Neel, M., & Ene, E. (2002). FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps. Retrieved 11/29/08, from www.umass.edu/landeco/research/fragstats/fragstats.html

McKelvey, K., & Pearson, D. (2001). Population estimation with sparse data: the role of estimators versus indices revisited. Canadian Journal of Zoology, 1754-1765.

Merenlender, A.M., S.E. Reed, and K.L. Heise. (2009). Exurban development influences woodland bird composition. *Landscape and Urban Planning* 92: 255-263.

Mitchell, D., Tjornehoj, J., & Baker, B. (1999). Beaver populations and possible limiting factors in Rocky Mountain National Park.

Montgomery, D.R. (1999). Process Domains and the River Continuum. Journal of the American Water Resources Association (JAWRA), 35 (2):397-410.

Naiman, R., Johnston, C., & Kelley, J. (1988). Alteration of North American streams by beaver. Bioscience, 38:753-762.

Nanus L, Williams MW, Campbell DH, Elliott EM, Kendall C. (2008). Evaluating regional patterns in nitrate sources to watersheds in National Parks of the Rocky Mountains using nitrate isotopes. Env. Sci. Technol. 42:6487-93

National Institute of Invasive Species Science (NIISS). USGS, Fort Collins Science Center. Accessed online (1/08) at: http://www.niiss.org/cwis438/websites/niiss/About.php?WebSiteID=1

National Park Service (NPS). Rocky Mountain National Park, Natural and Cultural Resources, Ecosystems, Plants, and Animals (Retrieved 2/14/09) http://www.nps.gov/archive/romo/resources/research/needs/ecosystems.html

National Research Council (NRC). (1995). Review of EPA's Environmental Monitoring and Assessment Program: Overall Evaluation. Washington, D.C.: National Academy Press.

Natural Resources Conservation Service (USDA). (2009). Colorado state-listed noxious weeds. (URL: http://plants.usda.gov/java/noxious?rptType=State&statefips=08).

Neel, MC, K McGarigal, and SA Cushman (2004) Behavior of class-level landscape metrics across gradients of class aggregation and area. *Landscape Ecology* 19: 435-455.

Neff, J.P., Ballentyne, A.P., Farmer, G.L., Mahowald, N.M., Conroy, J.L., Landry, C.C., Overpeck, J.T., Painter, T.H., Lawrence, C.R., and Reynolds, R.L.(2008). Increasing eolian dust deposition in the Western United States linked to human activity. Nature Geosciences, doi:10.1038/ngeo133.

Nelson, A. (2008). Travel time to major cities: A global map of Accessibility. Global Environment Monitoring Unit - Joint Research Centre of the European Commission, Ispra Italy. Available at http://gem.jrc.ec.europa.eu/

Nicholson, E., D. A. Keith, D. S. Wilcove (2009). Assessing the threat status of ecological communities. *Conservation Biology* 23(2)**:**259-274.

Noon, B. (2003). Conceptual issues in monitoring ecological resources. In D. Busch, & J. Trexler, Monitoring Ecosystems: Interdisciplinary Approaches for Evaluating Ecoregional Initiatives (pp. 27-72). Island Press.

Noon, B., & McKelvey, K. (2006). The process of indicator selection. In C. Aguirre, P. Bravo, P. Pellicane, D. Burns, & S. Draggan (Ed.), Monitoring Science and Technology Symposium: Unifying Knowledge for Sustainability in the Western Hemisphere (pp. 944-951). USDA Forest Service ProceedingsRMRS-P-42CD.

Noss, RF. (1990). Indicators for monitoring biodiversity: A hierarchical approach. *Conservation Biology* 4(4):355-364.

Novak, M. (1987). Beaver. In M. Novak, J. Baker, M. Obbard, & B. Malloch, Wild furbearer management and conservation in North America (pp. 283-312). Ontario Trappers Association and Ontario Ministry of Natural Resources.

Odell, E., & Knight, R. (2001). Songbird and medium-sized mammal communities associated with exurban development in Pitkin County, Colorado. Conservation Biology, 15 (4):1143-1150.

Oppenheimer, M., C. B. Epstein, and R. E. Yuhnke. (1985). Acid Deposition, Smelter Emissions, and the Linearity Issue in the Western United States. *Science*229:859-862.

Packard, F. (1947). A survey of the beaver population of Rocky Mountain National Park, Colorado. Journal of Mammology, 28:219-227.

Parsons, D., Swetnam, T., & Christensen, N. (1999).Use and limitations of historic variability concepts in managing ecosystems. Ecological Applications, 9:1177-1178.

Peinetti, H., Kalkhan, M., & Coughenour, M. (2002). Long-term changes in willow spatial distribution on the elk winter range of Rocky Mountain National Park (USA). Landscape Ecology, 17:341-354.

Peterson, S.A., Van Sickle, J., Herlihy, A.T., Hughes, R.M. (2007) Mercury concentration in fish from streams and rivers throughout the Western United States. Environmental Science and Technology 41:58-65.

Pettebone, D., Newman, P., Theobald, D.M. (2006) Quantifying recreation impacts along the Glacier Gorge trail. Final project report for the National Park Service.Colorado State University, Department of Natural Resources Recreation and Tourism, Fort Collins.

Pister, E. (2001). Wilderness fish stocking: history and perspective. Ecosystems, 4:279-286.

Poff, N.L., Olden, J.D., Merritt, D.M., and Pepin, D.M.(2007). Homogenization of regional river dynamics by dams and global biodiversity implications. Proceedings of the National Academy of Sciences 104(14): 5732-5737.

Reeves, G.H.; Hohler, D.B.; Larsen, D. P.; Busch, D. E.; Kratz, K.; Reynolds, K.; Stein, K. F.; Atzet, T.; Hays, P.; Tehan, M.. 2004. *Effectiveness Monitoring for the Aquatic and Riparian Component of the Northwest Forest Plan: Conceptual Framework and Options*. Gen. Tech. Rep. PNW-GTR-577. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 71 p.

Reeves, G.H., J.E. Williams, K.M. Burnett, and K. Gallo. (2006). The Aquatic Conservation Strategy of the Northwest Forest Plan. Conservation Biology, 20(2): 319-329.

Riitters, Kurt H.; Wickham, James D.; O'Neill, Robert V.; Jones, K. Bruce; Smith, Elizabeth R.; Coulston, John W.; Wade, Timothy G.; Smith, Jonathan H. (2002). Fragmentation of Continental United States Forests. *Ecosystems* 5: 815-822.

Riitters, K.H., J.D. Wickham, and T.G. Wade. (2009). An indicator of forest dynamics using a shifting landscape mosaic. *Ecological Indicators* 9(1): 107-117.

Riitters, K.H. and J.D. Wickham. (2003). How far to the nearest road? *Frontiers in Ecology and Environment* 1: 125-129.

Rutledge, C. R., & McLendon, T. (1996). An Assessment of Exotic Plant Species of Rocky Mountain National Park. Retrieved from Northern Prairie Wildlife Research Center

Online: http://www.npwrc.usgs.gov/resource/plants/explant/index.htm (Version 15DEC98)

Salas, D., Stevens, J., & Schulz, K. (2005). Rocky Mountain National Park, Colorado: 2001-2005 vegetation classification and mapping. Technical Memorandum 8260-05-02. Denver, CO: U.S. Bureau of Reclamation.

Sanchez-Montoya, M.M., M.R. Vidal-Abarca, T. Punti, J.M. Poquest, N. Prat, M. Rieradevall, J. Alba-Tercedor, C. Zamore-Munoz, M. Toro, S. Robles, M. Alvarez, M.L. Suarez. (2009). Defining criteria to select reference sites in Mediterranean streams. Hydrobiologica 619:39-54.

Sanderson, E.W., M. Jaiteh, M.A. Levy, K.H. Redford, A.V. Wannebo, and G. Woolmer. (2002). The human footprint and the last of the wild. *BioScience* 52(1): 891-904.

Schultz, M.T. (2001). A critique of EPA's index of watershed indicators. *Journal of Environmental Management,* 62: 429-442.

Seaber, P.R., Kapinos, F.P. and Knapp, G.L. (1987). *Hydrologic Unit Maps: U.S. Geological Survey,* Water-Supply Paper 2294, 63 pp.

Sickman, J. O., J. M. Melack, and D. W. Clow. (2003). Evidence for Nutrient Enrichment of High-Elevation Lakes in the Sierra Nevada, California. Limnology and Oceanography 48:1885-1892.

Sickman, J., Melack, J., & Stoddard, J. (2002). Regional analysis of inorganic nitrogen yield and retention in high-elevation ecosystems of the Sierra Nevada and Rocky Mountains. Biogeochemistry, 57-58:341-374.

Sibold, J.S., T.V. Veblen, K. Chipko, L. Lawson, E. Mathis, and J. Scott. (2007). Influences of secondary disturbances on lodgepole pine stands in Rocky Mountain National Park. *Ecological Applications* 17:1638-1655.

Slough, B., & Sadleir, R. (1977). A land capability classification system for beaver (*Castor canadensis* Kuhl). Canadian Journal of Zoology, 55:1324-1335.

Sowa, S.P., G. Annis, M.E. Morey, and D.D. Diamond. (2007). A Gap analysis and comprehensive conservation strategy for riverine ecosystems of Missouri. Ecological Monographs, 77(3): 301-334.

Stevenson, R.J. and F.R. Hauer. (2002). Integrating hydrogeomorphic and index of biotic integrity approaches for environmental assessment of wetlands. Journal of North American Benthological Society, 21(3): 502-513.

Stoddard, J. L., D. S. Jeffries, A. Lukewille, T. A. Clair, P. J. Dillon, C. T. Driscoll, M. Forsius, M. Johannessen, J. S. Kahl, J. H. Kellogg, A. Kemp, J. Mannio, D. T. Monteith, P. S. Murdoch, S. Patrick, A. Rebsdorf, B. L. Skjelkvale, M. P. Stainton, T. Traaen, H. van

Dam, K. E. Webster, J. Wieting, and A. Wilander. (1999). Regional trends in aquatic recovery from acidification in North America and Europe. Nature 401:575-578.

Stoddard, J., Larsen, D., Hawkins, C., & Johnson, R. N. (2006). Setting expectations for the ecological condition of streams: the concept of reference condition. Ecological Applications, 16:1267-1276.

Stoms, D. (2000). GAP management status and regional indicators of threats to biodiversity. Landscape Ecology, 15:21-33.

Taylor, P., Fahrig, L., Henein, K., & Merriam, G. (1993). Connectivity is a vital element of landscape structure. Oikos, 68:571-573.

Tiner, R.W. (2004). Remotely-sensed indicators for monitoring the general condition of "natural habitat" in watersheds: An application for Delaware's Nanticoke River watershed. Ecological Indicators, 4: 227-243.

Theobald, D. (2003). Targeting conservation action through assessment of protection and exurban threats. *Conservation Biology*, 17 (6):1624-1637.

Theobald, D. (2004). Placing exurban land-use change in a human modification framework. Frontiers in Ecology and the Environment, 2 (3):139-144.

Theobald, D. (2005). Landscape patterns of exurban growth in the USA from 1980 to 2020. *Ecology and Society*, 10 (1):32.

Theobald, D. and N.T. Hobbs . (2002). Functional definition of landscape structure using a gradient-based approach. In *Predicting species occurrences: Issues of accuracy and scale*, J. M. Scott, P.J. Heglund, M.L. Morrison, J.B. Haufler, M.G. Raphael, W.A. Wall, and F.B. Samson (eds). Pgs. 667-674.

Theobald, D., Miller, J., & Hobbs, N. (1997). Estimating the cumulative effects of development on wildlife habitat. Landscape and Urban Planning, 39 (1):25-36.

Theobald, D., Norman, J., & Sherburne, M. (2006, April 17). FunConn v1 User's Manual: ArcGIS Tools for Functional Connectivity Modeling. 47. Fort Collins, Colorado: Natural Resource Ecology Lab.

Theobald, D.M., J.B. Norman, E. Peterson, A.Wade, and S. Ferraz. (2006). Functional Linkage of Watersheds and Streams (FLoWs) User's Manual: Network-based ArcGIS tools to analyze freshwater ecosystems. May 2006. www.nrel.colostate.edu/projects/starmap

Theobald, D., & Romme, W. (2007). Expansion of the U.S. wildland-urban interface. Landscape and Urban Planning, 83:340-354.

Theobald, D., Spies, T., Kline, J., Maxwell, B., Hobbs, N., & Dale, V. (2005). Ecological support for rural land-use planning. Ecological Applications, 15 (6):1906-1941.

Theobald, D.M., J.B. Norman, III, and P. Newman. (2010). Estimating visitor use of protected areas by modeling accessibility: a case study in Rocky Mountain National Park, Colorado, USA. *Journal of Conservation Planning* (accepted 8 December 2009).

Turner, M.G. (2005) Landscape ecology: what is the state of the science? *Annual Review of Ecology, Evolution, and Systematics* 36: 319-344.

Unified Classification of Direct Threats, http://www.iucn.org/themes/ssc/sis/classification.htm, IUCN-CMP. (2006).

U.S. Climate Change Science Program (USCCSP), 2008: Preliminary review of adaptation options for climate-sensitiveecosystems and resources. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Juli , S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, 873 pp.

U.S. Department of Agriculture (USDA; 2008). Stream simulation: an ecological approach to providing passage for aquatic organisms at road-stream crossings. U.S. Forest Service National Technology and Development Program 7700-Transportation Management, 0877 1801- SDTDC.

U.S. Department of Transportation (DOT). (2007, January). National Transportation Atlas Database (NTAD) 2007 CD. Research and Innovative Technology Administration/ Bureau of Transportation Statistics.

U.S. EPA. Guidelines for Ecological Risk Assessment. (1998). U.S. Environmental Protection Agency, Risk Assessment Forum, Washington, DC, EPA/630/R095/002F.

U.S. EPA. (1993). Environmental Monitoring and Assessment Program. EPA/620/R-94/022.

U.S. EPA. (2002). A Framework for Assessing and Reporting on Ecological Condition. Young, T.F. & Sanzone, S., eds.Ecological Reporting Panel, Ecological Processes and Effects Committee, EPA Science Advisory Board, Washington, DC. EPA-SAB-EPEC-02-009.

U.S. General Accounting Office (GAO). (1994). National Park Service: Activities outside park borders have caused damage to resources and will likely cause more. Washington, D.C.: U.S. General Accounting Office.

Usenko, S., D. H. Landers, P. G. Appleby, and S. L. Simonich. (2007). Current and Historical Deposition of PBDEs, Pesticides, PCBs, and PAHs to Rocky Mountain National Park. Environmental Science & Technology 41:7235-7241.

Van Wagtendonk, J. W., Benedict, J. M. (1980). Travel time variationon backcountry trails. Journal of Leisure Research, 12:99–106.

Vasconcelos, D., & Calhoun, A. (2004). Movement patterns of aduclt and juvenile *Rana sylvatica* (LeConte) and *Ambystoma maculatum* (Shaw) in three restored seasonal pools in Maine. Journal of Herpetology, 38:551-561.

Veblen, T.T. (2000). Climate and human influences on fire regimes in ponderosa pine forests in the Colorado front range. Ecological Applications 10:1178-1195.

Veblen, T.T., K.S. Hadley, E.M. Nel, T. Kitzberger, M. Reid, and R. Villalba (1994). Disturbance regimes and disturbance interactions in a Rocky-Mountain sub-alpine forest. Journal Ecology 82:125-135.

VEMAP participants (1996). The VEMAP Phase I database: an integrated input dataset for ecosystem and vegetation modeling for the conterminous United States (http://www.cgd.ucar.edu/vemap/).

Vitousek, P. M., J. D. Aber, R. W. Howarth, G. E. Likens, P. A. Matson, D. W. Schindler, W. H. Schlesinger, and D. G. Tilman. (1997). Human alteration of the global nitrogen cycle: its causes and consequences. Ecological Applications 7:737-750.

Wade, A.A., and D.M. Theobald. (*in press*). Residential encroachment on U.S. protected areas. *Conservation Biology*.

Watson, A.E., D.N. Cole, D.L. Turner and P.S. Reynolds (2000) Wilderness Recreation Use Estimation: A Handbook of Methods and Systems. USDA Forest Service, General Technical Report RMRS-GTR-56. Rocky Mountain Research Station, Ogden, Utah.

Watts, R.D., R.W. Compton, J.H. McCammon, C.L. Rich, S.M. Wright, T. Owens, and D.S. Ouren. (2007). Roadless space of the conterminous United States. *Science* 316, 736-738.

Weathers, K.C., Simkin, S.M., Lovett, G.M., Lindberg, S.E. (2006) Empirical modeling of atmospheric deposition in mountainous landscapes. *Ecological Applications*: 16(4):1590-1607.

Westbrook, C.J., D.J. Cooper, and B.W. Baker. (2006). Beaver dams and overbank floods influence groundwater-surface water interactions of a RockyMountain riparian area. *Water Resources Research* 42: 4560.

Western Governors Association (WGA). (2008, June 29). Western Governors Association Wildlife Corridors Initiative Report. Retrieved October 12, 2008, from http://www.westgov.org/wga/initiatives/corridors/index.htm

Wheatley, M. (1997). Beaver, *Castor canadensis,* home range size and patterns of use in the taiga of southeastern Manitoba: II. Sex, age, and family status.*Canadian Field-Naturalist*, 111:211-216.

White, M.L. and C. Maurice. (2004). CrEAM: a method to predict ecological significance at the landscape scale. Unpublished report, EPA.

Wickham, J.D., K.H. Riitters, T.G. Wade, and C. Homer. (2008). Temporal change in fragmentation of continental U.S. forests. *Landscape Ecology* 23: 891-898.

Wiens, J.A. (2002). Riverine landscapes: Taking landscape ecology into the water. Freshwater Biology, 47: 501-515.

Williams, M., Bardsley, T., & Rikkers, M. (1998). Overestimation of snow depth and inorganic nitrogen wetfall using NADP data, Niwot Ridge, Colorado. Atmospheric Environment, 32 (22):3827-3833.

Williams, M., Knauf, M., et al. (2007). Nitrate content and potential microbial signature of rock glacier outflow, Colorado Front Range. Earth Surface Processes and Landforms, 1455.

Wolfe, A. P., A. C. Van Gorp, and J. S. Baron. (2003). Recent ecological and biogeochemical changes in alpine lakes of Rocky Mountain National Park (Colorado, USA): a response to anthropogenic nitrogen deposition. Geobiology 1:153-168.

Woods, S. W. (2000). Hydrologic effects of the Grand Ditch on streams and wetlands of Rocky Mountain National Park, Colorado. M.S. Thesis. Colorado State University, Fort Collins, CO, USA.

Woods, S.W. and D.J. Cooper. (2005). Hydrologic factors affecting initial willow seedling establishment along a subalpine stream, Colorado, U.S.A. *Arctic, Antarctic, and Alpine Research* 37(4): 636-643.

Woods, S.W., L.H. MacDonald, and C.J. Westbrook. (2006). Hydrologic interactions between an alluvial fan and a slope wetland in the central Rocky Mountains, USA. *Wetlands* 26(1):230-243.

Woolmer, G., S.C. Trombulak, J.C. Ray, P.J. Doran, M.G. Anderson, R.F. Baldwin, A. Morgan, and E.W. Sanderson. (2008). Rescaling the human footprint: A tool for conservation planning at an ecoregional scale. *Landscape and Urban Planning* 87: 42-53.

Yeardley, R. B., Jr.; Lazorchak, J. M.; Paulsen, S. G. (1998) Elementalfish tissue contamination in northeastern U.S. lakes: evaluationof and approach to regional assessment. Environmental Toxicology and Chemistry17:1875-1884.

Technical Appendix 1: Stream Connectivity Methods

This document is a brief description of procedures involved in classifying 1:24K streams in Rocky Mountain National Park (ROMO) with native and non-native interactions. The objective of this analysis is to provide information where native fish are isolated from non-native and where they co-exist. This analysis relies on the Functional Linkages of Watersheds (FLoWS) data structure to route native and non-native fish up and down stream restricting movement based on documented movement barriers (e.g., waterfalls). The starting point of this analysis began by generating a FLoWS landscape network, which builds reach to reach relationships based on the topology of the NHD 1:24K stream polylines. These relationships assume that movement throughout the stream network is unrestricted. To better inform the FLoWS with movement restrictions in ROMO, a stream barriers dataset (Figure 41) was used to alter relationships so that fish can move downstream through a barrier but not upstream. With the network developed, native and non-native fish observations were joined to the FLoWS network edges (stream reaches) using the fish observation datasets supplied by ROMO (Figure 42). This resulted in an a-spatial representation of native and non-native fish distributions within ROMO, but does not account for movement between observations (gaps in observation data) and potential overlap. This was address by taking the native and non-native designations and routing them up and down stream via the FLoWS edges and barriers dataset. The outline below describes this analysis in detail:

I. FLoWS network development
   1) Networking NHD 1:24K
      a. Generate a Landscape network using the enhanced NHD 1:24K stream reaches using the FLoWS tool *Polyline to Landscape Network.*
      b. Check and clean up network topology issues
      a. Check for network errors using the FLoWS tool *Check Network Topology,* which identifies stream reaches with connectivity errors. The stream reaches with topology errors are fixed resulting in a topologically correct network and relationships.
      b. Generate main channels through braided stream channels using the FLoWS tool *Clean Braided Channels,* which builds a new relationships with braided stream channel relationships removed.
      c. Build stream barriers into network relationships
         i. Attribute stream reaches with barrier information.
         ii. The landscape network edges were attributed with barrier information using the FLoWS tool *Snap Points to Landscape Network Edges,* which finds the nearest edge to each barrier and attributes the barrier point with the edge_rid and the point’s distance ratio from the end of an edge.
         iii. Alter the relationships table to reflect barrier conditions within the full network.
            1. Edges to edge relationships (via the relationships table) are removed based on edges that have barriers. This “breaks” the network where barriers exist, preventing movement upstream.

II. Process ROMO fish observation datasets

1) The ROMO streams and lakes datasets are a version of NHD 1:24K stream and water bodies that have been attributed with observed fish spp. (species_1, species_2, species_3, and species_4). The four fish spp. attributes for the streams and lakes datasets where grouped into native and non-native classes based on the species codes from the four original attributes, resulting in a 0 if no fish were observed (native or non-native) and a 1 if a fish was observed (native or non-native). The native fish attribute entailed Colorado River Cutthroat (species code CRC) and the Green Back Cutthroat (Species code CBC). The non-native fish attribute entails all other fish documented within the datasets, which include:
   a. Brook Trout (BKT)
   b. Brown Trout (BNT)
   c. Cutthroat Trout (CUT)
   d. Rainbow Trout (RBT)
   e. Yellowstone Cutthroat Trout (YCT)

III. Network attribution

1) The stream and lake fish observation datasets where merged into two rasters representing native and non-native fish occurrences for water bodies and stream reaches (romo_nat and romo_nonat). These two rasters were evaluated using *Zonal Statistics as Table* using the edges_rid as the zone raster and the romo_nat and romo_nonat rasters as the value rasters. This resulted in two tables (romo_nat.dbf and romo_nonat.dbf) which were joined to the FLoWS edges feature class (joining on RID) and romo_native and romo_non_native fields calculated to 0 or 1.

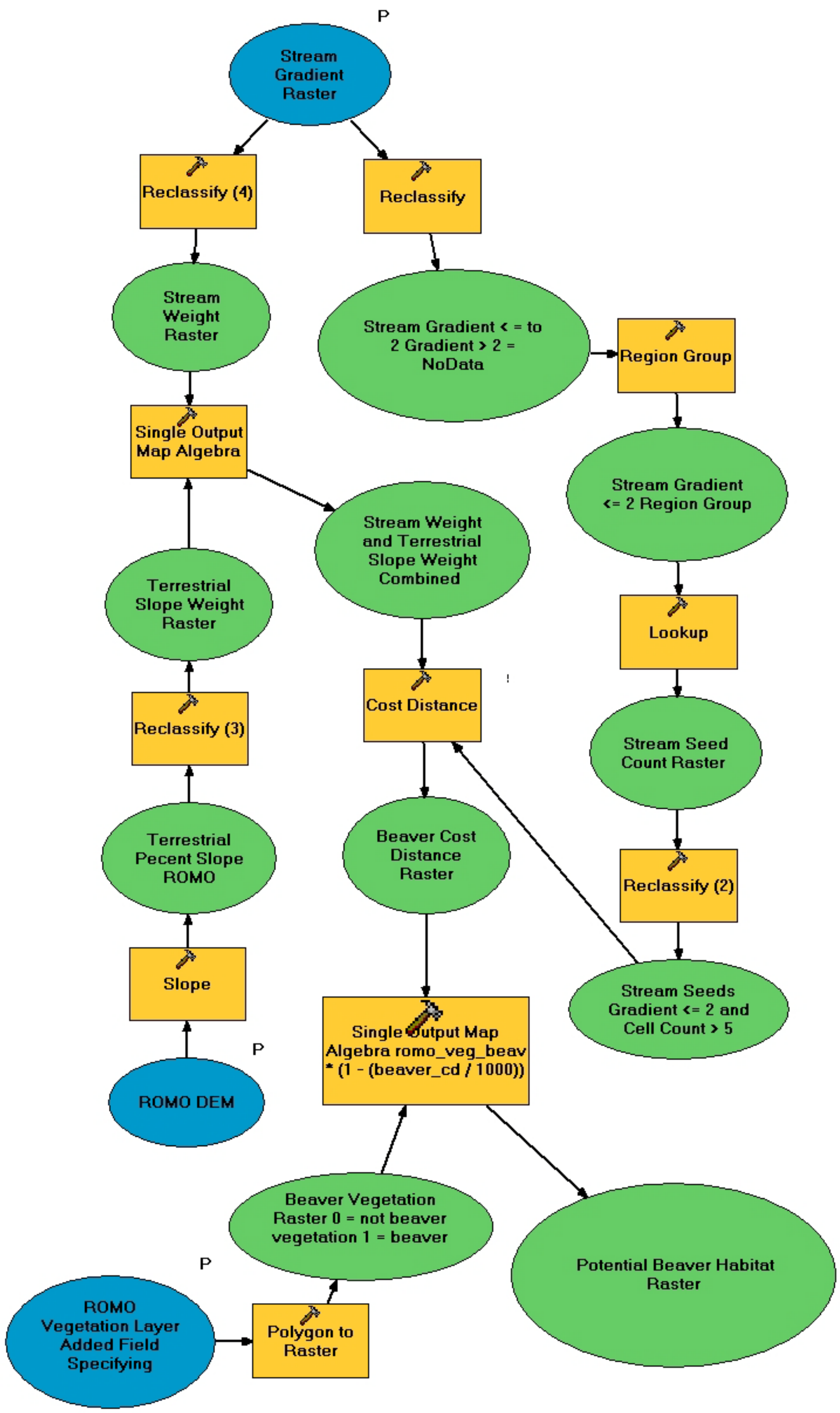
IV. Network analysis/fish distribution modeling

1) Fish movement analysis
   a. The first step of the network analysis is to accumulate the ROMO native and non-native fields downstream with the FLoWS tool *Accumulate Values Downstream*. This analysis generates a new field that contains the total number of reaches upstream that have native or non-native fish populations.
   b. To capture the upstream and downstream movement potential from observation locations, the two downstream accumulation fields were accumulated upstream using the FLoWS tool *Accumulate Values Upstream*, which captures fish movement upstream stopping at barriers.
   c. To assess the potential spatial distribution of native and non-native fish within the network, two fields were added to the FLoWS edges feature class that capture the global influence of native and non-native fish distributions (romo_nat and romo_nonat). These fields were calculated with a 0 (absent) or a 1 (present) by assessing if the sum of the downstream and upstream accumulations were > 0.
   d. The global native and non-native attributes were broken into four classes based on the relationships between romo_nat and romo_nonat using the flowing rules:
   a. If romo_nat > 0 and romo_nonat = 0 (calculate to ‘Native Only’)
   b. If romo_nat > 0 and romo_nonat > 0 (calculate to ‘Native / Non-native’)
   c. If romo_nat = 0 and romo_nonat > 0 (calculate to ‘Non-native Only’)
   d. If romo_nat = 0 and romo_nonat = 0 (calculate to ‘No Fish recorded’)

Technical Appendix 2. Life-zone Class Delineation Methods

I. Methods
  a. Generate life-zone classes lookup table for ROMO vegetation shapefile (romoveg.shp) supplied by ROMO.
    i. The VegReclass attribute (romoveg.shp) was summarized in ArcGIS 9.2 Analysis Tools > Statistics > Summary Statistics, generating a new table (vegreclass_summary.dbf), which provides all unique vegetation classes (n = 28) and the backbone of the lookup table.
    ii. Develop six life-zone classes and one class non-life zone class that will be merged with adjacent life-zone classes.
      1. Six life-zone classes
        a. Alpine (GRIDCODE = 1)
        b. Savanna (GRIDCODE = 2)
        c. Lower Montane (GRIDCODE = 3)
        d. Open Water (GRIDCODE = 4)
        e. Riparian/Wetland (GRIDCODE = 5)
        f. Upper Montane (GRIDCODE = 6)
      2. Non-life zone
        a. Barren/human modified (GRIDCODE = 0)
    iii. Assign each of the 28 unique VegReclass values in the vegreclass_summary.dbf one of the seven life-zone classes
  b. Develop ROMO life-zone shapefile
    i. Add GRIDCODE field to romoveg.shp which will hold a numeric value associated with the life-zone class
    ii. Join vegreclass_summary.dbf to romoveg.shp joining on Vegreclass field from both tables.
    iii. Calculate GRIDCODE equal to life-zone gridcode
    iv. Convert romoveg.shp to a raster data structure with raster cell values equal to the GRIDCODE field with a cell size (10 meters) and extent set to ROMO Digital Elevation Model (DEM) to match the other rasters involved in the NRCA project.
    v. Assign non-life-zones (GRIDCODE 0) with adjacent life-zone classes with the Spatial Analyst Tools > Distance > Euclidean Allocation (ecu_lif_zn)
    vi. Convert ecu_lif_zn to a feature class (romo_life_zones.shp) generalizing polygon boundaries instead of retaining gridded boundaries.

Technical Appendix 3: Beaver Suitable Habitat Modeling



ArcCatalog Operations

```
ProjectRaster_management C:\Beaver\romo_dem_gcs
C:\Beaver_3\romo_dem_NAD
PROJCS['NAD_1983_UTM_Zone_13N',GEOGCS['GCS_North_American_1983',DATUM[
'D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],
PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION[
'Transverse_Mercator'],PARAMETER['False_Easting',500000.0],PARAMETER['
False_Northing',0.0],PARAMETER['Central_Meridian',-
105.0],PARAMETER['Scale_Factor',0.9996],PARAMETER['Latitude_Of_Origin'
,0.0],UNIT['Meter',1.0]];IsHighPrecision NEAREST 9.372539 # #
"PROJCS['NAD_1983_UTM_Zone_13N',GEOGCS['GCS_North_American_1983',DATUM
['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]]
,PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION
['Transverse_Mercator'],PARAMETER['False_Easting',500000.0],PARAMETER[
'False_Northing',0.0],PARAMETER['Central_Meridian',-
105.0],PARAMETER['Scale_Factor',0.9996],PARAMETER['Latitude_Of_Origin'
,0.0],UNIT['Meter',1.0]];-5120900 -9998100
450445547.391054;#;#;0.001;#;#;IsHighPrecision"
```

```
ProjectRaster_management C:\Beaver\strm_grad_per
C:\Beaver_3\strm_grad_NAD
"PROJCS['NAD_1983_UTM_Zone_13N',GEOGCS['GCS_North_American_1983',DATUM
['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]]
,PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION
['Transverse_Mercator'],PARAMETER['False_Easting',500000.0],PARAMETER[
'False_Northing',0.0],PARAMETER['Central_Meridian',-
105.0],PARAMETER['Scale_Factor',0.9996],PARAMETER['Latitude_Of_Origin'
,0.0],UNIT['Meter',1.0]];-5120900 -9998100
450445547.391054;#;#;0.001;#;#;IsHighPrecision" NEAREST 8.97133 # #
"PROJCS['NAD_1983_Albers',GEOGCS['GCS_North_American_1983',DATUM['D_No
rth_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIME
M['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Albe
rs'],PARAMETER['False_Easting',0.0],PARAMETER['False_Northing',0.0],PA
RAMETER['Central_Meridian',-
96.0],PARAMETER['Standard_Parallel_1',29.5],PARAMETER['Standard_Parall
el_2',45.5],PARAMETER['Latitude_Of_Origin',23.0],UNIT['Meter',1.0]];-
16901100 -6972200 266467840.990852;#;#;0.001;#;#;IsHighPrecision"
```

```
Project_management C:\Beaver\rmnp_veg.shp C:\Beaver_3\rmnp_veg_NAD
PROJCS['NAD_1983_UTM_Zone_13N',GEOGCS['GCS_North_American_1983',DATUM[
'D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],
PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION[
'Transverse_Mercator'],PARAMETER['False_Easting',500000.0],PARAMETER['
False_Northing',0.0],PARAMETER['Central_Meridian',-
105.0],PARAMETER['Scale_Factor',0.9996],PARAMETER['Latitude_Of_Origin'
,0.0],UNIT['Meter',1.0]] #
PROJCS['NAD_1983_Albers',GEOGCS['GCS_North_American_1983',DATUM['D_Nor
th_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM
['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Alber
```

s'],PARAMETER['False_Easting',0.0],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-96.0],PARAMETER['Standard_Parallel_1',29.5],PARAMETER['Standard_Parallel_2',45.5],PARAMETER['Latitude_Of_Origin',23.0],UNIT['Meter',1.0]]

ArcMap operations

Project_management rmnp_bdry_albers C:\Beaver_3\rmnp_bdry_nad PROJCS['NAD_1983_UTM_Zone_13N',GEOGCS['GCS_North_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PARAMETER['False_Easting',500000.0],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-105.0],PARAMETER['Scale_Factor',0.9996],PARAMETER['Latitude_Of_Origin',0.0],UNIT['Meter',1.0]] # PROJCS['NAD_1983_Albers',GEOGCS['GCS_North_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Albers'],PARAMETER['False_Easting',0.0],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',-96.0],PARAMETER['Standard_Parallel_1',29.5],PARAMETER['Standard_Parallel_2',45.5],PARAMETER['Latitude_Of_Origin',23.0],UNIT['Meter',1.0]]

Buffer_analysis rmnp_bdry_nad C:\Beaver_3\rmnp_bdry_buff_1K.shp '1000 Meters' FULL ROUND NONE #

Executing (Buffer_3): Buffer rmnp_bdry_nad C:\Beaver_3\rmnp_bdry_buff_1K.shp "1000 Meters" FULL ROUND NONE #

ExtractByMask_sa strm_grad_nad rmnp_bdry_buff_1K C:\Beaver_3\romo_strm_grd

Executing (ExtractByMask_4): ExtractByMask strm_grad_nad rmnp_bdry_buff_1K C:\Beaver_3\romo_strm_grd

Resample_management romo_dem_nad C:\Beaver_3\romo_dem_9m C:\Beaver_3\romo_strm_grd NEAREST

Executing (Resample_6): Resample romo_dem_nad C:\Beaver_3\romo_dem_9m C:\Beaver_3\romo_strm_grd NEAREST

ExtractByMask_sa romo_dem_9m rmnp_bdry_buff_1K C:\Beaver_3\romo_dem

Executing (ExtractByMask_7): ExtractByMask romo_dem_9m rmnp_bdry_buff_1K C:\Beaver_3\romo_dem

The grid cells of romo_strm_grd and romo_dem were not aligned. They were off by approximately 3 m. Using the Georeferencing tool, we aligned romo_dem with romo_strm_grd. We named the aligned DEM romo_dem1

```
Reclassify_sa romo_strm_grd Value '0 2 1;2 68.139595031738281 NODATA'
C:\Beaver_3\rmnp_strm_0-2 DATA
```

Executing (Reclassify_8): Reclassify romo_strm_grd Value "0 2 1;2 68.139595031738281 NODATA" C:\Beaver_3\rmnp_strm_0-2 DATA

```
RegionGroup_sa rmnp_strm_0-2 C:\Beaver_3\seeds_temp EIGHT WITHIN
ADD_LINK #
```

Executing (RegionGroup_9): RegionGroup rmnp_strm_0-2 C:\Beaver_3\seeds_temp EIGHT WITHIN ADD_LINK #

```
Lookup_sa seeds_temp COUNT C:\Beaver_3\rmnp_strm_ct
```

Executing (Lookup_10): Lookup seeds_temp COUNT C:\Beaver_3\rmnp_strm_ct

```
Reclassify_sa rmnp_strm_ct VALUE '1 5 NODATA;5 1181 1'
C:\Beaver_3\strm_seeds DATA
```

Executing (Reclassify_11): Reclassify rmnp_strm_ct VALUE "1 5 NODATA;5 1181 1" C:\Beaver_3\strm_seeds DATA

```
Slope_sa romo_dem1.img C:\Beaver_3\rmnp_slope_9m PERCENT_RISE 1
```

Executing (Slope_12): Slope romo_dem1.img C:\Beaver_3\rmnp_slope_9m PERCENT_RISE 1

```
Reclassify_sa rmnp_slope_9m Value '0 2 10;2 10 30;10 20 50;20
1492.6871337890625 150' C:\Beaver_3\slope_wt DATA
```

Executing (Reclassify_13): Reclassify rmnp_slope_9m Value "0 2 10;2 10 30;10 20 50;20 1492.6871337890625 150" C:\Beaver_3\slope_wt DATA

```
Reclassify_sa romo_strm_grd Value '0 2 0;2 10 1;10 20 3;20
68.139595031738281 100' C:\Beaver_3\strm_wt DATA
```

Executing (Reclassify_14): Reclassify romo_strm_grd Value "0 2 0;2 10 1;10 20 3;20 68.139595031738281 100" C:\Beaver_3\strm_wt DATA

```
SingleOutputMapAlgebra_sa 'con (isnull (strm_wt), slope_wt, strm_wt)'
C:\Beaver_3\strm_slop_wt #
```

```
Executing (SingleOutputMapAlgebra_15): SingleOutputMapAlgebra "con
(isnull (strm_wt), slope_wt, strm_wt)" C:\Beaver_3\strm_slop_wt #


CostDistance_sa strm_seeds strm_slop_wt C:\Beaver_3\beaver_cd 1000 #

Executing (CostDistance_16): CostDistance strm_seeds strm_slop_wt
C:\Beaver_3\beaver_cd 1000 #


PolygonToRaster_conversion rmnp_veg_NAD Beaver
C:\Beaver_3\romo_veg_beav CELL_CENTER NONE C:\Beaver_3\beaver_cd

Executing (PolygonToRaster_17): PolygonToRaster rmnp_veg_NAD Beaver
C:\Beaver_3\romo_veg_beav CELL_CENTER NONE C:\Beaver_3\beaver_cd


SingleOutputMapAlgebra_sa 'romo_veg_beav * (1 - (beaver_cd / 1000))'
C:\Beaver_3\veg_cost #

Executing (SingleOutputMapAlgebra_18): SingleOutputMapAlgebra
"romo_veg_beav * (1 - (beaver_cd / 1000))" C:\Beaver_3\veg_cost #
```

Patch statistics by drainage in ROMO.

Total Area = the total area of potentially suitable beaver habitat in the drainage

patches = the number of patches of potentially suitable beaver habitat in the drainage

Ave. Area = average area of the patches in the drainage

Std. Area = the standard deviation of the areas of patches in the drainage

Ave. Score = the average beaver habitat suitability score of patches in the drainage

Std. Score = the standard deviation of average beaver habitat suitability scores of patches in the drainage

Status 1999-2000 = Active, if evidence of current beaver activity was observed in any patch in the drainage during surveys in 1999-2000. If evidence of past beaver activity was observed in any patch in a drainage, it is classified as Past Activity, and if no surveys were conducted in any of the patches in a drainage, it is classified as No Survey.

Drainage Name	Total Area (HA)	# Patches	Ave. Area (HA)	Std. Area (HA)	Ave Score	Std. Score	Status 1999-2000
Colorado River	188.92	47	4.02	10.29	0.60	0.31	Active
Onahu Creek	97.74	7	13.96	35.12	0.36	0.22	Active
Baker Creek	83.73	1	83.73	0.00	0.67	0.00	Active
Fall River	61.67	14	4.40	11.08	0.30	0.25	Active
Big Thompson River	56.05	20	2.80	8.56	0.54	0.27	Active
Hague Creek	43.90	8	5.49	8.17	0.50	0.21	Active
Cub Creek	41.94	12	3.50	8.34	0.51	0.18	Active
North Saint Vrain Creek	24.60	6	4.10	9.69	0.44	0.18	Active
North Inlet	23.47	11	2.13	6.11	0.46	0.25	Active
Mill Creek	13.15	5	2.63	5.61	0.27	0.30	Active
Boulder Brook	8.68	6	1.45	2.90	0.47	0.19	Active
Black Canyon Creek	8.27	1	8.27	0.00	0.72	0.00	Active
Cow Creek	3.77	4	0.94	0.97	0.58	0.18	Active
Beaver Creek	0.18	3	0.06	0.08	0.21	0.12	Active
Cache la Poudre River	98.21	14	7.01	18.29	0.50	0.23	Past Activity
Willow Creek	33.85	5	6.77	12.02	0.52	0.08	Past Activity
East Inlet	18.05	20	0.90	2.05	0.58	0.26	Past Activity
Beaver Brook	12.71	16	0.79	1.37	0.38	0.24	Past Activity
Glacier Creek	11.36	20	0.57	0.75	0.52	0.25	Past Activity
Hidden Valley Creek	9.29	10	0.93	1.61	0.47	0.22	Past Activity
Hunters Creek	5.76	7	0.82	1.02	0.42	0.32	Past Activity
Sandbeach Creek	5.45	5	1.09	1.96	0.31	0.22	Past Activity
North Fork Big Thompson River	4.35	16	0.27	0.44	0.36	0.20	Past Activity
Wind River	1.58	5	0.32	0.36	0.30	0.19	Past Activity
Roaring Fork	0.20	1	0.20	0.00	0.35	0.00	Past Activity
Cony Creek	5.13	5	1.03	1.08	0.54	0.24	No Activity

Drainage Name	Total Area (HA)	# Patches	Ave. Area (HA)	Std. Area (HA)	Ave Score	Std. Score	Status 1999-2000
Ouzel Creek	2.18	1	2.18	0.00	0.61	0.00	No Activity
Chapin Creek	17.27	2	8.64	10.77	0.59	0.02	No Survey
Cascade Creek	16.41	13	1.26	2.47	0.36	0.23	No Survey
Mummy Pass Creek	12.38	3	4.13	3.08	0.53	0.14	No Survey
Tonahutu Creek	9.79	30	0.33	0.57	0.35	0.24	No Survey
Fish Creek	6.76	5	1.35	2.62	0.49	0.23	No Survey
South Fork Cache la Poudre River	6.66	10	0.67	0.96	0.46	0.23	No Survey
Sawmill Creek	2.72	2	1.36	1.86	0.31	0.40	No Survey
Little Columbine Creek	2.57	2	1.28	1.44	0.57	0.06	No Survey
Roaring River	1.57	5	0.31	0.56	0.11	0.09	No Survey
Bighorn Creek	1.41	4	0.35	0.24	0.41	0.23	No Survey
Columbine Creek	1.15	2	0.58	0.21	0.41	0.13	No Survey
West Creek	0.89	3	0.30	0.50	0.31	0.30	No Survey
Ptarmigan Creek	0.81	3	0.27	0.28	0.53	0.03	No Survey
Shelf Creek	0.80	3	0.27	0.24	0.45	0.27	No Survey
Phantom Creek	0.80	3	0.27	0.19	0.40	0.11	No Survey
Tyndall Creek	0.35	3	0.12	0.13	0.12	0.09	No Survey
Ranger Creek	0.32	1	0.32	0.00	0.47	0.00	No Survey
Chiquita Creek	0.21	1	0.21	0.00	0.25	0.00	No Survey
Squeak Creek	0.15	2	0.08	0.10	0.25	0.03	No Survey
Big Dutch Creek	0.08	1	0.08	0.00	0.17	0.00	No Survey
Echo Creek	0.06	1	0.06	0.00	0.14	0.00	No Survey
Timber Creek	0.04	1	0.04	0.00	0.17	0.00	No Survey
Icy Brook	0.02	1	0.02	0.00	0.01	0.00	No Survey
UNKNOWN***	92.71	165	0.56	1.19	0.39	0.25	

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National Park Service
U.S. Department of the Interior

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