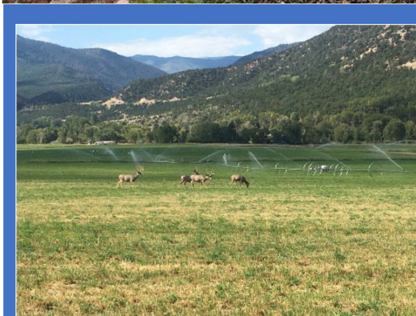
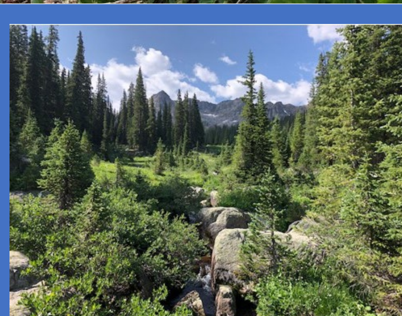
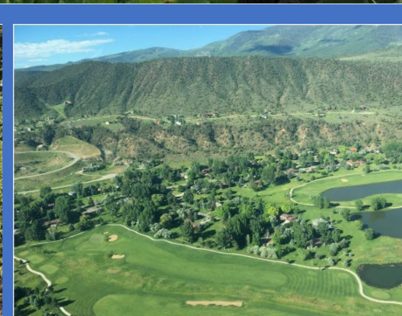
Roaring Fork Watershed Biodiversity & Connectivity Study







2022

CNHP's mission is to advance the conservation of Colorado's native species and ecosystems through science, planning, and education for the benefit of current and future generations.

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Front Cover: Top photo: view facing east from Frigid Air Pass of columbine (*Aquilegia coerulea*) and ridge between Belleview Mountain and Maroon Peak. Bottom photos left to right: elk summer grazing in an irrigated pasture, rich Spruce-Fir forests and wetlands of Chapman Gulch, and an aerial view from plane of the lower Roaring Fork valley between Glenwood Springs and Carbondale. © Andrea Schuhmann

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EXECUTIVE SUMMARY

"...because migrating ungulates must plod hoof by hoof across increasingly human-impacted landscapes, their conservation status can serve as an early warning signal for the erosion of wildlife habitats and their functional connectivity (Middleton et al. 2020)" Kaufman et al. 2021.

Background

The Roaring Fork Watershed is among the most ecologically intact and varied landscapes in Colorado. Elevations ranging from 5,700 feet to over 14,000 feet above sea level support several distinct native plant communities, from sagebrush, oak, and pinyon-juniper in the low elevations, transitioning to aspen and conifer forests as elevation increases, before finally reaching up to alpine tundra on the highest peaks, ridges, and passes. These communities in turn support a remarkable diversity of animal life, from jackrabbits to bighorn sheep, hundreds of bird species, and thousands of insects. Altogether these species knit the landscape together into a living whole. The Watershed is among the wettest watersheds in the state with wetlands and riparian areas representing known biodiversity hotspots. This species-rich landscape is both an important natural resource and a stewardship responsibility that is best approached on a solid scientific footing.

The Watershed's 928,640-acre landscape supports over 32,000 people as well as abundant wildlife populations. Iconic species such as elk and mule deer can be found in most habitats throughout the Watershed, while bighorn sheep roam the high country. Declines in the elk and mule deer populations have become a concern in recent decades; bighorn sheep, once common, are now rare in the Watershed. These concerning downward trends in wide-ranging common animals, coupled with a community commitment to use the best available science to protect and restore biodiversity, led in 2018 to the creation of the non-profit Watershed Biodiversity Initiative (WBI). WBI's purpose is to support a study to identify landscape-scale areas to protect and restore in order to maintain the Watershed's biodiversity. This report is the culmination of the Roaring Fork Watershed Biodiversity and Connectivity Study.

WBI and partners' overarching goal was to develop a science-based strategy for the protection and restoration of natural biodiversity and habitat connectivity on a landscape scale. In order to achieve this goal, they determined that they needed to work with independent researchers to conduct a study that would objectively identify and map biodiversity conservation and restoration priorities from a landscape perspective. The concept was that the study would be designed and implemented in concert with local funders, scientific experts, and stakeholders, and that development and implementation of methods would be an ongoing collaboration over the life of the study. The purpose of this approach was to foster widespread acceptance and use of the process and the results. To that end, WBI engaged Colorado Natural Heritage Program (CNHP) to lead the study and organized a Science Team (Appendix A) to oversee and participate in development of the study design.

Because the Watershed is so large and the interests of the participants were so broad, the Science Team determined that the best way to frame the study was through the use of "focal species." The highest priority focal species were defined as **mule deer (*Odocoileus hemionus*)**, **elk (*Cervus elaphus*)**, and **bighorn sheep (*Ovis canadensis*)**. The primary reasons for this decision were widespread concern over declining populations of these iconic animals, and urgency of land-use decisions with potential to affect these species. Also, there was the thought among Project and Science Teams that, by identifying high quality, well-connected areas across the multiple habitat types used by these wide-ranging species, habitats important to many other species would be included as well. The ungulate-focused analyses were supplemented by additional existing data layers representing biodiversity importance (rare and imperiled species and habitats, climate change resilience), and key areas identified as important (specific places such as Audubon's Important Bird Areas, ungulate calving areas mapped by Colorado Parks and Wildlife, CPW)—in other words, species and places whose needs may not be adequately captured through a broad-scale habitat management approach.

Goal and Objectives

The overarching goal of the project was to develop a science-based set of models and maps to identify areas for the protection and restoration of natural biodiversity and habitat connectivity on a landscape scale. Study objectives were:

1. Identify high quality habitats for focal species, and places on the landscape that provide connectivity between these locations.
2. Map high priority places where conservation and restoration could enhance landscape function and expand core habitats.
3. Use existing data to combine other significant biodiversity information with focal species data into a watershed-scale conservation and restoration priority map.

Methods Overview

The study consisted of field data collection in 2019-2021 and multiple GIS analyses. The key analyses and mapped outputs (models) of the study were 1) **Habitat Quality** for elk, mule deer, and bighorn, and 2) **Conservation Importance**—critical areas for focal species as well as other biodiversity values, culminating in 3) **Conservation and Restoration Priorities** across the landscape (Figure ES-1).

Over the summers of 2019 and 2020, field biologists collected vegetation data for forage resources (grasses, forbs, shrubs, and trees) at 129 randomly selected sites across the Watershed. These data formed the basis of the forage quality models for elk and mule deer during winter and growing seasons (Figure ES-2). The models were validated in the field at an additional 102 randomly selected sites during the summer of 2021. Additional data layers representing shelter, water availability, forage contributions from agricultural fields, and anthropogenic disturbance were combined with the forage quality models to create habitat quality models (Figures ES-3 and ES-4). These models were classified into relative quality categories of Low, Moderate, and High, using distinct rule sets specific to species and season, and then connectivity between moderate and high quality habitat areas was modeled (Figure ES-4). Bighorn were not included in this step because of the availability of existing habitat models for this species. To generate the habitat quality model for bighorn, existing habitat models (from CPW and Rocky Mountain Wild) were combined, escape habitat was added, and the resulting model (Figure ES-5) was classified into the same relative quality categories of Low, Moderate, and High as was used for elk and mule deer.

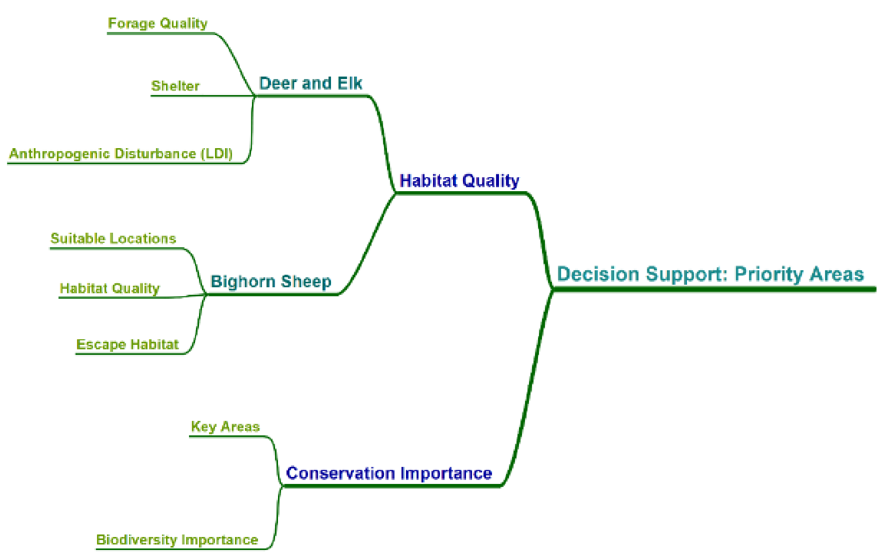

Figure ES-1. Schematic showing sequence of analyses used to create the Watershed Conservation and Restoration Priorities map.

To complement the habitat quality analyses for the focal species, we added "Conservation Importance," which incorporates rare species, small-scale habitats such as wetlands, climate resilient areas, and locally significant natural areas. We created two GIS layers to map Conservation Importance (Figure ES-5): Key

Areas and Biodiversity Importance. Key Areas are small and/or discrete places that have critical importance to a functioning natural landscape. These included 1) birthing areas, severe winter and winter concentration areas for elk, mule deer, and bighorn, as mapped by CPW; 2) modeled potential local movement corridors; 3) places where the landscape inhibits the potential for population movements and range shifts in response to climate change (TNC-CRCS 2021); and 4) sites of local significance (Audubon Important Bird Areas, nature preserves). Biodiversity Importance included CNHP data on rare and imperiled species and plant communities, wetlands, and landscape diversity (to represent areas more likely to be resilient to climate change, TNC-CRCS 2021).

All these data layers were combined into the Watershed Conservation and Restoration Priorities map ("priorities map," Figure ES-6, Table ES-1) using a decision matrix based on relative habitat quality for the focal ungulates and conservation importance scores (Figure ES-7). The final priorities map highlights areas of high-quality ungulate habitat that also support additional high biodiversity values, as well as areas of degraded ungulate habitat quality that nonetheless have significant conservation importance for other biodiversity values. This map offers a landscape-scale view of opportunities for employing strategies to conserve important, high-quality places and restore degraded habitat in places that still support significant biodiversity values.

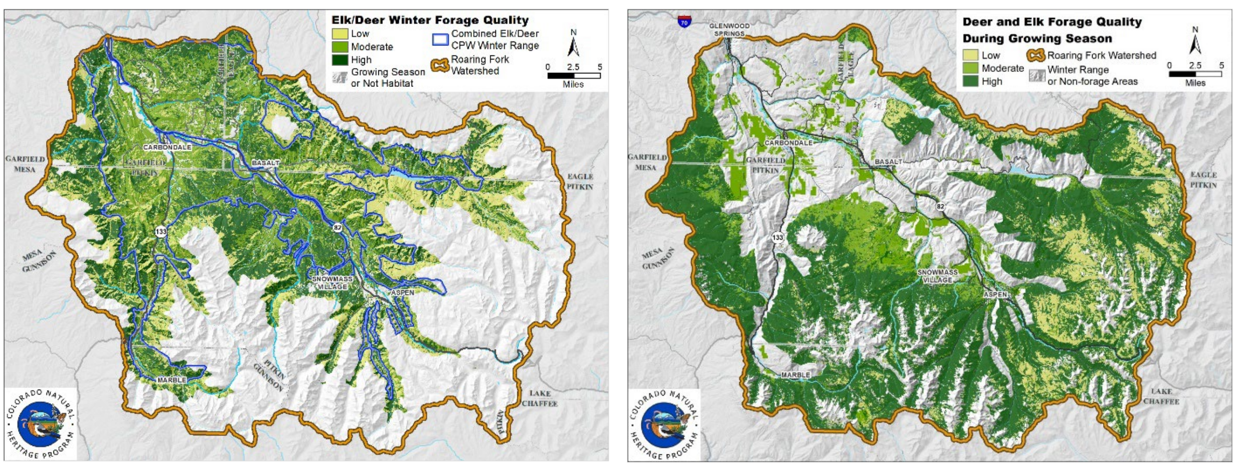

Figure ES-2. Forage quality model for elk and mule deer during winter (left) and growing season (right).

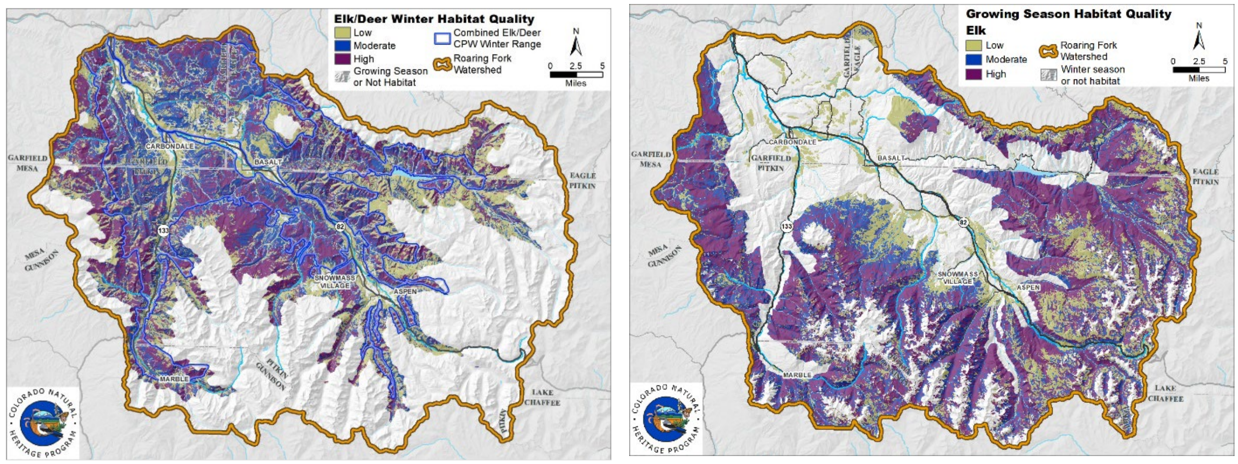

Figure ES-3. Habitat quality model for elk and mule deer during winter (left) and for elk during growing season (right).

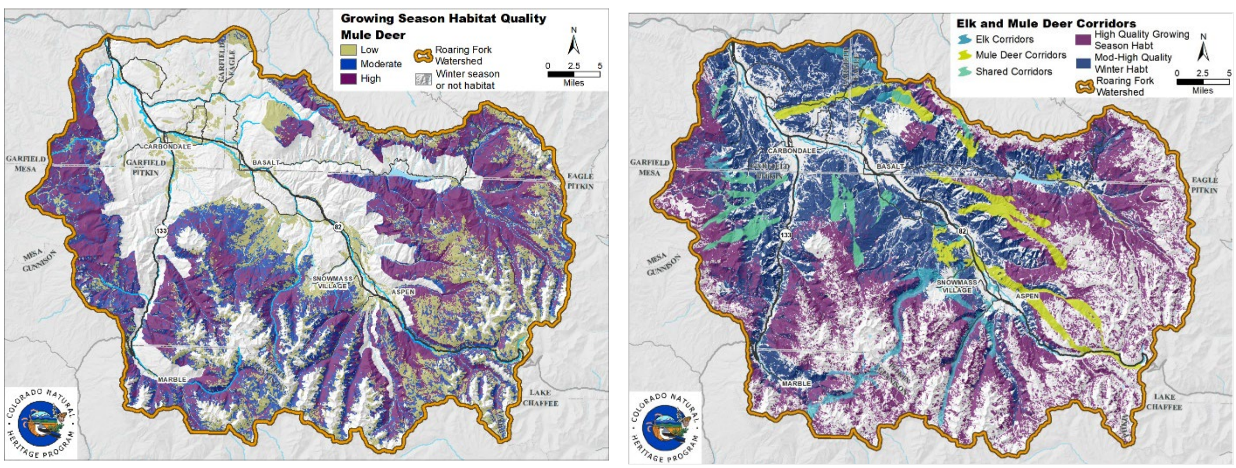

Figure ES-4. Habitat quality model for mule deer during growing season (left); movement corridors for elk and mule deer (right).

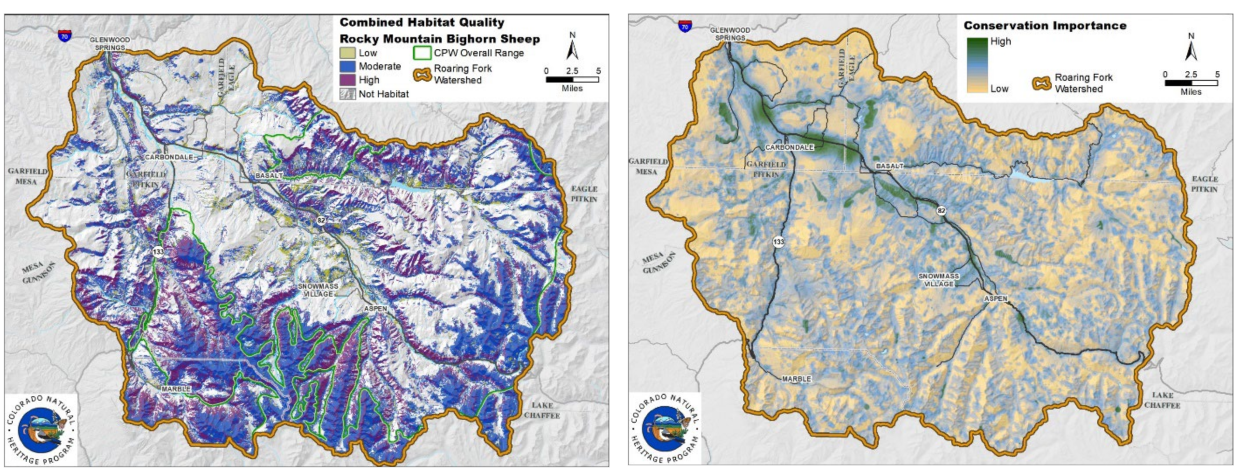

Figure ES-5. Habitat quality model for bighorn sheep (left); Conservation Importance model (right).

Table ES- 1. Legend definitions for Conservation and Restoration Priorities map.

Matrix Color	Definition
(dark purple)	Highest quality habitat for focal ungulates AND highest priority for biodiversity.
(medium purple)	High or moderate quality habitat for focal ungulates AND moderate priority for biodiversity.
(light purple)	High or moderate habitat quality for focal ungulates that are generally unfragmented but lacking other biodiversity values.
(yellow)	Lower quality habitat for focal ungulates and fewer biodiversity values documented.
(dark orange)	Lower habitat quality for focal ungulates but very high conservation importance for other biodiversity values.
(orange)	Important for biodiversity but improvements in habitat quality/connectivity are likely needed for focal ungulates.
(gray)	Not practical conservation or restoration opportunities due to the dominance of urban or other developed areas and established transportation networks.

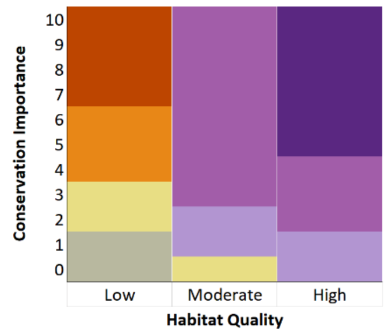

Figure ES-6. Decision matrix used to create Conservation and Restoration Priorities map.

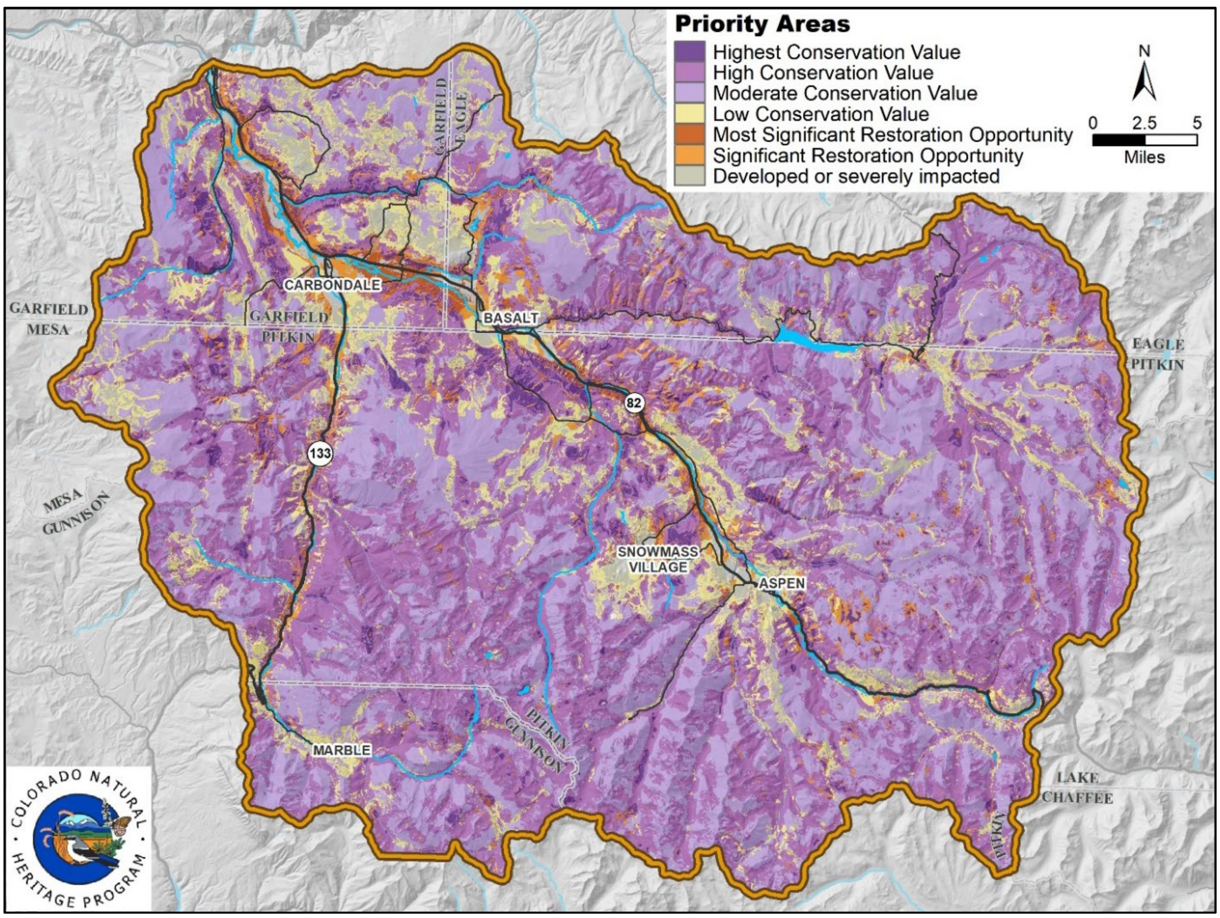

Figure ES- 7. Conservation and restoration priorities for the Roaring Fork Watershed.

Key Findings

1. Overall, the vast majority of the Roaring Fork Watershed supports land with Moderate, High, or Highest Conservation Value, and these areas are well-distributed across the watershed. Significant opportunities exist to restore degraded habitats and improve connectivity, especially along major transportation corridors and near developed areas.

2. Forage quality does not appear to be a limiting factor by itself in either winter or growing season ranges for elk and mule deer according to our models. Seventy percent of modeled winter range and 80% of known winter range (based on CPW maps) was classified as high or moderate forage quality, and 87% of the growing season has high to moderate forage quality. Within each seasonal range, the dominant ecological systems (for example, Spruce-Fir, Aspen, Oak/Mixed Shrub) are comprised primarily of moderate or high quality forage.

3. The value of moderate and high quality forage is reduced when availability of other habitat resources (water, shelter) and anthropogenic disturbance are considered in the habitat quality models for elk and mule deer. Sixty-four percent of modeled winter range and 69% of known winter range (based on CPW maps) was classified as high or moderate habitat quality, and 74% of the growing season has high to moderate habitat quality. Even with this quality reduction compared to the forage quality models, the majority of all seasonal ranges are comprised primarily of moderate and high quality habitat. Dominant ecological systems in each seasonal range are also still comprised primarily of moderate and high quality habitat.

4. The Watershed has an abundance of wetlands, especially in the high country. Wetlands within the ecotone between Spruce-Fir and Alpine systems were consistently observed by the field biologists to offer very abundant palatable forage, and to be very heavily used by ungulates. These are, therefore, high priority places for minimizing human disturbance (e.g., via trails, roads).

5. According to the habitat quality model for modeled winter range, Aspen is the dominant ecological system in the transition zone between known winter range and growing season range. This transition zone is likely to be increasingly important to ungulates in winter as climate change warms temperatures and reduces snowpack. The majority of this area currently supports moderate or high quality habitat; maintaining habitat quality in these areas warrants attention.

6. Private lands represent approximately one-third of modeled winter range, but almost half of known winter range for elk and mule deer. Within both modeled and known winter range, there is very little difference in the relative percentage of moderate and high quality habitats on private lands compared to public lands. Because habitats on private lands are more vulnerable to loss (conversion to development, for example), supporting habitat conservation on these lands is very important for wintering ungulates. Within the growing season range, private lands make up a much smaller proportion of the area compared to public lands; the majority of moderate and high quality habitats are on public lands.

7. There are a number of areas within the Watershed where higher quality habitats are bisected by well-traveled roads (especially Highways 82 and 133) and other human developments. These places offer excellent opportunities to improve landscape connectivity. Places where movement pinch points occur between high quality habitat amidst a mix of land ownership types offer excellent opportunity for public/private partnerships. Even small patches of high quality habitat are used by elk and mule deer as they move among habitats. Improving connectivity (safe animal passage and use) in places such as these would increase the value of these habitats.

8. The habitat model for bighorn sheep identifies several areas with moderate to high quality habitat where sheep are not currently present. These may present opportunities to expand the bighorn population if CPW determines that such a strategy is justifiable.

Recommendations

The Big Picture

The results of our study and the feedback we received during our test drives with the Science Team, private owners of large holdings, local caucuses, and more, led WBI and CNHP to four "big ideas" for moving forward with conserving biodiversity in the Roaring Fork Watershed.

Big idea # 1 – "Stitching it back together." Reconnect large landscapes that have been fragmented in the Watershed. This will improve habitat quality for deer and elk, and therefore hopefully restore and maintain healthy populations of these species. Using the forage and habitat quality models, CPW's SAM maps, and our connectivity model can help identify places where improved connectivity is needed. Examples of key opportunities include areas around Cattle Creek, Missouri Heights, and Carbondale (see Figure 24), but there are others. Opportunities for public/private partnerships exist in many of these places.

Big Idea # 2 – Guide development and land conservation decisions to avoid additional fragmentation and maintain connectivity amongst swaths of large intact landscapes. Any introduction of additional infrastructure or disturbance (including land development, roads and trails) will affect habitat quality. Careful consideration of potential impacts are especially needed for areas associated with ungulate winter concentration areas and severe winter range, areas that serve as movement corridors through or between high or moderate quality habitats, areas where restoration could raise habitat quality scores and/or improve connectivity, and wetlands and wet meadows (especially in the ecotone between subalpine forests and the alpine). Public/private partnerships will be key to success in many of these places.

Big Idea # 3 – Protect large, isolated landscapes for bighorn sheep. Because disease transmission is an issue for this species, these populations benefit from isolation. Recovering the State's and region's bighorn sheep population is a widely shared goal among conservationists and wildlife managers. This goal serves as a clear rallying point to generate support for protecting and restoring the natural biodiversity that is critical to healthy ecosystem functioning.

Big Idea # 4 – "Rewet the sponge." Protect and/or restore wetlands throughout the Watershed. Wetlands, especially in growing season and transitional areas offer abundant high quality forage. Nearly one-third of the Watershed is blanketed with upper to high elevation conifer forests where 80% of annual precipitation is captured as snow and preserved in cool, shady conditions. Wetlands within the ecotone between Spruce-Fir and Alpine systems were consistently observed by our field team to be very heavily used by ungulates. Minimizing human disturbance (e.g., via trails, roads) is particularly important in these areas. Elk and mule deer herds have calves during the time of year that they use these high elevation habitats, and they are especially sensitive to disturbance at this time. Restoring degraded wetlands can slow the water down, increase infiltration into the soil, assimilate nutrients, and improve forage and habitat for elk, mule deer, and an abundance of other wildlife species.

Additional Recommendations

1. Plan for the future, but act in the present. The maps and data contained herein represent current conditions. We expect these condition to change, albeit in unknown ways, in the coming years as the climate continues to change. Anticipating these changes will be an important component of planning for conservation and restoration strategies. For example, our models suggest that Aspen areas within the modeled winter range will become more important habitat in future winters. Meanwhile, though, continuing to strive for improved quality where habitats occur now, as in the known winter range, is needed. High and moderate quality habitats associated with known severe winter and winter concentration areas are high priorities for conservation, as well as restoration of connectivity where needed.

2. Use these data in combination with other resources when evaluating potential conservation or restoration projects. There are at least two studies currently underway that will provide additional insights to the quality of habitats and connectivity within the Watershed when results become available. These include a collar study of elk movement by CPW, and a wetland study by CNHP. Results from CPW's collar study are still at least two years out. Final data from CNHP's wetland study are expected in 2022.

3. Periodic vegetation-based monitoring would be useful to detect changes in habitat quality over time. Monitoring every ten years would likely be sufficient. Other monitoring opportunities would include after disturbances (e.g., wildfire, flood, extended extreme drought), when conservation or restoration projects are being undertaken, or if observed changes warrant review of habitat condition. The detailed field data collection used to build the forage quality model is not necessary to repeat for periodic monitoring assessments. The condensed field methods used to validate the model (described in Appendix C) would be a relatively efficient means of quickly evaluating a site for basic forage quality. The most difficult component to assess is palatability. Creating a handbook or "cheat sheet" of the most palatable species would support monitoring even by trained volunteers.

4. Revisit study assumptions and analyses when CPW's animal movement and habitat use data become available.

5. Consult with CNHP for proper use and interpretation of the maps and data provided with this study as a regular practice to ensure the study is used to its fullest capacity. Spatial data are freely available from CNHP, and WBI will be supporting our biologists to provide as-needed assistance through the end of 2022. The spatial data layers developed during this study have been provided to the Science Team members, and will be uploaded into CODEX (https://codex.cnhp.colostate.edu) for general public use.
6. These maps and data layers were developed to be used at a scale of approximately 1:24,000. On-the-ground field assessments are recommended for all site-specific projects.

Conclusion

This study did not seek to address reasons behind herd decline(s) or evaluate ideal population numbers for focal species in the Watershed. Nonetheless, the strategies outlined in this report—protecting high quality habitat and connectivity where possible, and improving habitat quality and connectivity where needed—will contribute toward the future viability of elk, mule deer, and bighorn herds, as well as all the other components of the Watershed's biodiversity.

The maps and spatial data layers created during this project provide a science-based means of identifying and prioritizing biodiversity conservation and restoration needs within the context of the entire Watershed. Though individual stakeholder's priorities may vary depending on mission, goals, and interests, these products can ensure that the Watershed's interested parties and decision makers share the same basic understanding of biodiversity and connectivity across the Watershed. It is the hope of WBI and all the partners who participated in the study that this document and the spatial data layers that accompany it will support the development of the multi-partner collaborations needed to steward the Roaring Fork Watershed's biodiversity heritage now and into the future.

LETTER FROM THE DIRECTOR, WBI

"Generate the best available science to identify, protect, and restore natural biodiversity on a landscape scale." This is the essential goal of the Roaring Fork Watershed Biodiversity and Connectivity Study (the Study). Such an ambitious initiative emerged out of a critical mass of individuals and organizations sharing a common concern about the decline of Elk, Mule Deer, and Bighorn Sheep populations in the Roaring Fork Watershed. These three species ultimately became the Study's focus as proxies for much of the Watershed's biodiversity—all the region's native species, including around 278 birds, 70 mammals, 15 reptiles, amphibians and fish, 22 trees, hundreds of other plants, and thousands of insects and fungi. This concern was amplified by a more general awareness of biodiversity declines globally and regionally.

Locally the concern was given a voice by one lead agency's policy[1] to apply the best available science to protect and restore biodiversity. The report that follows is the best effort of a collaborative Science Team convened by the nonprofit organization Watershed Biodiversity Initiative. The collaboration served to frame and guide the Study conducted over three years by the Colorado Natural Heritage Program, arguably Colorado's primary source for biodiversity science.

You will find detailed within the Study some key scientific findings and big picture ideas for conservation action informed by the science. Ideally, conservation action informed by the Study is initiated collaboratively within the community by neighborhood groups, conservation organizations, agricultural cooperatives, agencies, local governments, academic entities, and individuals. Anyone with an interest in biodiversity conservation in the Watershed can be informed and equipped by the Study to conceive, advocate for, and engage in a landscape-scale biodiversity protection or enhancement project.

Go to the body of the report for the science in all its informative specificity and detail. But stay with me briefly in this Foreword to get some perspective on the overarching story that you may also find emerging from the science. Just remember, the science is the most reliable part, but some informed interpretation, the intuitive part, can also be helpful in understanding the Study while also identifying areas for further scientific study. Grasping the story before all the pieces are in place can be helpful. This is often accomplished by those with deep knowledge of a subject and the ability to accurately integrate information before all the data are in.

The Story of Biodiversity in the Valley

The Roaring Fork Watershed is endowed with abundant good habitat. Quality forage does not appear to be a limiting factor in summer or winter. Aspen forests, about 15% of the Watershed, are very important for the focal species (and biodiversity generally), especially in winter-summer transition periods. The importance of Aspen will only increase with climate warming and drying as the extent of winter habitat begins to creep upslope into these forests. Wetlands and riparian ecosystems occupy a small fraction of our Watershed (less than 5%), yet they offer habitat benefits that far exceed their physical size. These wet

[1] https://pitkincounty.com/DocumentCenter/View/10317/20160804-OSTB-Biodiversity-Policy?bidId=

systems, small in size but rich with biodiversity, are largely supplied with water by the upper elevation conifer forests that cover about a third of our Watershed. Though these forests don't always offer the best forage, here is where most of the watershed's annual precipitation is collected and held as snow, the primary snowpack that recharges the wet places during the warmer months. Capturing the meltwater from winter snowpack with wetland restoration, particularly at higher elevations, effectively creates a "second snowpack." These wetness elements illustrate how small areas can be rich with life and lower quality habitat can provide vital ecosystem services. All the pieces of a natural landscape have value.

Our working lands offer value as well. Elk and deer are common sights in pastures along roadways. "They like alfalfa and pasture grass" is a logical conclusion. Consider, though, that only about 2% of the watershed is irrigated pastureland, and once the hay is harvested, there's nothing left to eat. The subtleties that emerged peripheral to the Study are that a simple diet of non-native forage is not as nutritious or appropriate as the wide variety of native plants that elk and deer evolved eating while moving across large natural landscapes. A sedentary life and a simple diet diminishes their fitness and health. Wildlife grazing on private pastures also competes with the ranch economy. Looking further though, agricultural lands do provide access to the water and cover of riparian ecosystems and easy passage across valleys to public lands on the valley sides. And when forage is available it provides some nutrition, albeit not ideal or natural. Society can and often does value agricultural lands for both the food produced and the ecosystem services provided to wildlife. Conservation easements on agricultural lands recognize these values. Also, the opportunity exists for some agricultural lands in the right circumstances to be restored to native habitat, primarily benefiting biodiversity.

We are fortunate in that our Watershed retains healthy landscapes that stretch from the Crystal to the Fryingpan. Even though primary roadways and human developments fragment high quality habitats, there are plenty of opportunities to protect and/or improve habitat, including restoring landscape scale swaths of habitat by building connectivity over and under roadways. Private lands are critical for conservation because they contain half the occupied winter range for elk and deer, offer many options for public / private partnerships to improve the status of our declining herds, and are far more vulnerable to loss than public lands. And while landscape scale connectivity of habitats is desirable in many ways, there are sometimes reasons to conserve some isolated patches of habitat. Consider the bighorn sheep: they numbered in the millions across the western U.S. as recently as the 1880's. Today's populations are seriously diminished to a single digit percentage of what they once were. With intensive management, Colorado's bighorn herds, numbering as few as 2,200 in 1970, have rebounded to around 7,000 animals. But much work remains before this species, our state mammal, can be considered secure. The Study provides hope by identifying several landscape scale opportunities for bighorn sheep recovery and expansion by identifying places with suitable habitat where herds could potentially be restored.

What We Can Do

Here is a distillation of the Study's key findings into a handful of conservation actions. As with the Study itself, collaboration among stakeholders is needed to bring a project to fruition in a way that maximizes success. Note that the Study and all its sophisticated map layers are intended to identify conservation opportunities. Collaborative community engagement will then support successful conservation action and minimize conflict. Collaborative conservation is an intended outcome of the Study, and the maps and data are decidedly and intentionally lacking in any regulatory capacity.

1. **Stitch** fragmented landscapes back together. Highway overpass and underpass structures could be installed where mapping indicates that adjacent high quality habitats are isolated by roadways and high roadkill counts reveal a propensity for animals (elk, deer) to move between habitat blocks.
2. **Guide development or conservation** actions by convening appropriate stakeholders to identify development sites least impactful to biodiversity and conversely identifying where protection and restoration of landscape-scale habitats is least likely to conflict with current or future development projects. For example, a desired trail from a community to a destination would use the Study map layers to determine the trail route and ideally a complementary habitat enhancement project that together benefit people and biodiversity.
3. **Establish landscape-scale biodiversity protection and restoration as the consensus priority** in select, appropriate areas of the Watershed.
4. **Protect** large, isolated landscapes for bighorn sheep recovery by engaging appropriate stakeholders to select a few large landscapes among several options. The maps already identify the opportunities for restoring and expanding bighorn sheep populations.
5. **Re-saturate the landscape "sponge."** Reclaim wetlands by working collaboratively with experts and stakeholders to choose subdrainages in the watershed that are below average for wetness. Then consult the Study map layers to determine ideal sites to maximize water retention (the second snowpack) and benefit multiple interests, such as irrigators, municipal water users, fishing, livestock grazing permitees, hunters, bird conservationists, elk, deer, bighorn sheep recovery efforts, and more.

A Final Word

The Roaring Fork Watershed Biodiversity and Connectivity Study is a living document. Just as ecosystems are dynamic over time, the Study is designed to be replicable as well as adaptable to new information and refinements. Keep the Study dynamic and responsive with regular review and refinement, and plan its replication at reasonable intervals. With the Roaring Fork Watershed Biodiversity and Connectivity Study in hand, we can lay claim to being well informed by the best available science. A widely held motivation to value wildlife and wild landscapes unites our Watershed community. Now the Biodiversity Study, backed up by the Colorado Natural Heritage Program science support team, sets us up to be a community of informed, motivated, and capable environmental stewards with a landscape-scale perspective.

Tom Cardamone
Watershed Biodiversity Initiative

ACKNOWLEDGEMENTS

The authors of this study would like to sincerely thank Tom Cardamone, Executive Director of the Watershed Biodiversity Initiative (WBI), for envisioning this comprehensive, watershed-wide study focused on identifying key areas where protection and restoration are needed to conserve the biodiversity and ecological vitality of the region. Tom was instrumental in drumming up interest, support, and input from the Science Team members, landowners, land managers, and the broader public. We are grateful to the members of the Science Team and the WBI Board for sharing their intimate knowledge and love of the Roaring Fork Watershed, while also providing technical guidance and thorough review of the study's methods, analyses, and results throughout the project's many stages. The scope of this project would not have been possible without participation of several of the area's large-acreage private landowners and land managers. Private lands are key determinants of habitat quality and quantity for a countless array of wildlife, plants and wild communities, and the Roaring Fork Watershed is of course no exception. We would like to thank the generous members of the Roaring Fork Community who provided our field ecologists with housing and invaluable first-hand knowledge of the trends and changes they have witnessed, knowledge that at times spanned multiple generations. And lastly, the authors would like to share their overall gratitude for the opportunity to spend the last several years with boots-on-the-ground working collaboratively with knowledgeable, dedicated members of the conservation and Roaring Fork communities in an ecologically marvelous and inspiring landscape.

Funding for the Study was from both public and private sources. Public funds supported 56% of the study, and the remaining 44% came from 24 private contributions. Of the public funds, 44% came from Pitkin County, 55% from the U.S. Environmental Protection Agency, and important participation from the Town of Carbondale and City of Aspen. Pitkin County and its Open Space and Trails Program deserves great credit for providing the initial interest and substantial financial traction for the Biodiversity Study. The many private donors deserve equal credit for believing in the value of the study as displayed in their generosity of funding and spirit.

INTRODUCTION

Background

The Roaring Fork Watershed is among the most ecologically intact and varied landscapes in Colorado. Elevations ranging from 5,700 feet to over 14,000 feet above sea level support several distinct native plant communities, from sagebrush, oak, and pinyon-juniper in the low elevations, transitioning to aspen and conifer forests as elevation increases, before finally reaching up to alpine tundra on the highest peaks, ridges, and passes (Figure 1). These communities in turn support a remarkable diversity of animal life, from jackrabbits to bighorn sheep, hundreds of bird species, and thousands of insects. Altogether these species knit the landscape together into a living whole. The Watershed is among the wettest watersheds in the state with wetlands and riparian areas representing known biodiversity hotspots. This species-rich landscape is both an important natural resource and a stewardship responsibility that is best approached on a solid scientific footing.

The Watershed's 928,640-acre landscape consists of three major river basins—the Fryingpan, Roaring Fork, and Crystal Rivers—and supports over 32,000 people as well as abundant wildlife populations. Human communities, primarily clustered in the valley bottoms, enjoy access to vast public land holdings throughout the Watershed (Figure 2). Iconic species such as elk and mule deer can be found in most habitats throughout the Watershed, while bighorn sheep roam the high country. Declines in the elk population have become a concern in recent decades. Colorado Parks and Wildlife (CPW) reported that the elk in the Roaring Fork and Eagle valleys experienced a 50% reduction in their population since 2000, from a peak of nearly 20,000 to around 10,000 in 2018 (Millhouser 2019). A similar trend has appeared with mule deer; a 2020 report on the Basalt Mule Deer Unit stated that a reduction in carrying capacity due to loss of habitat quantity and quality had noticeably reduced the mule deer population (Mao 2020). Bighorn sheep, once common, are now rare in the Watershed—CPW estimates 210 individuals (pers. com J. Mao, CPW, Nov. 2021).

These concerning downward trends in wide-ranging common animals, coupled with a community commitment to use the best available science to protect and restore biodiversity, led in 2018 to the creation of the non-profit Watershed Biodiversity Initiative (WBI). WBI's purpose is to support a study to identify landscape-scale areas to protect and restore in order to maintain the Watershed's biodiversity. This report is the culmination of the Roaring Fork Watershed Biodiversity and Connectivity Study.

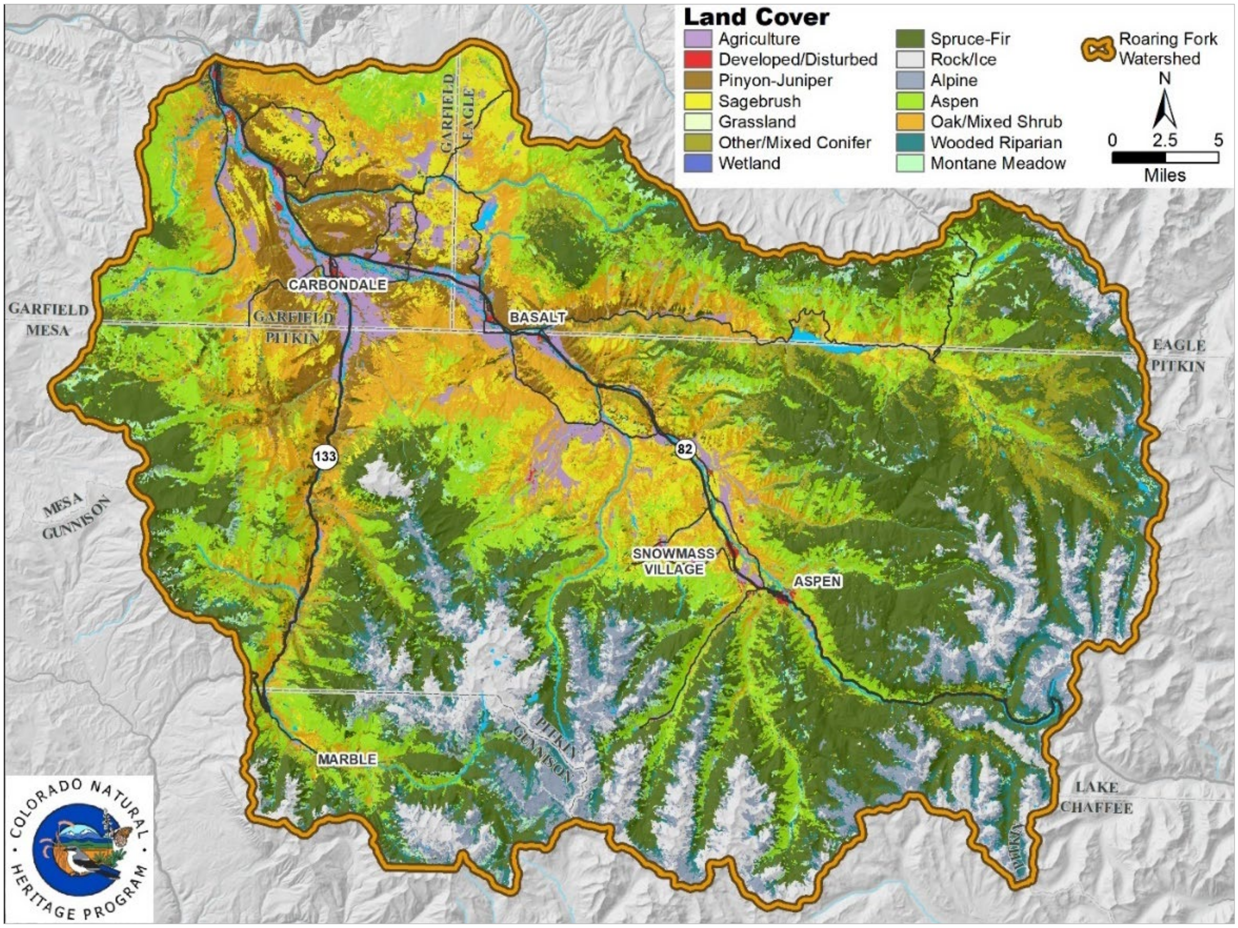

Figure 1. Land cover in the Roaring Fork watershed. Source: SWReGAP.

WBI and partners' overarching goal was to develop a science-based strategy for the protection and restoration of natural biodiversity and habitat connectivity on a landscape scale (https://www.watershedbiodiversityinitiative.org/study). In order to achieve this goal, they determined that they needed to work with independent researchers to conduct a study that would objectively identify and map biodiversity conservation and restoration priorities from a landscape perspective. The concept was that the study would be designed and implemented in concert with local funders, scientific experts, and stakeholders, and that development and implementation of methods would be an ongoing collaboration over the life of the study. The purpose of this approach was to foster widespread acceptance and use of the process and the results. To that end, WBI engaged Colorado Natural Heritage Program (CNHP) to lead the study and organized a Science Team (Appendix A) to oversee and participate in development of the study design. An informal network of conservation-oriented Stakeholders was informed about the study, solicited for advice, and in some cases engaged to contribute to secondary elements of the study (e.g., species of interest that fell outside the scope of this study).

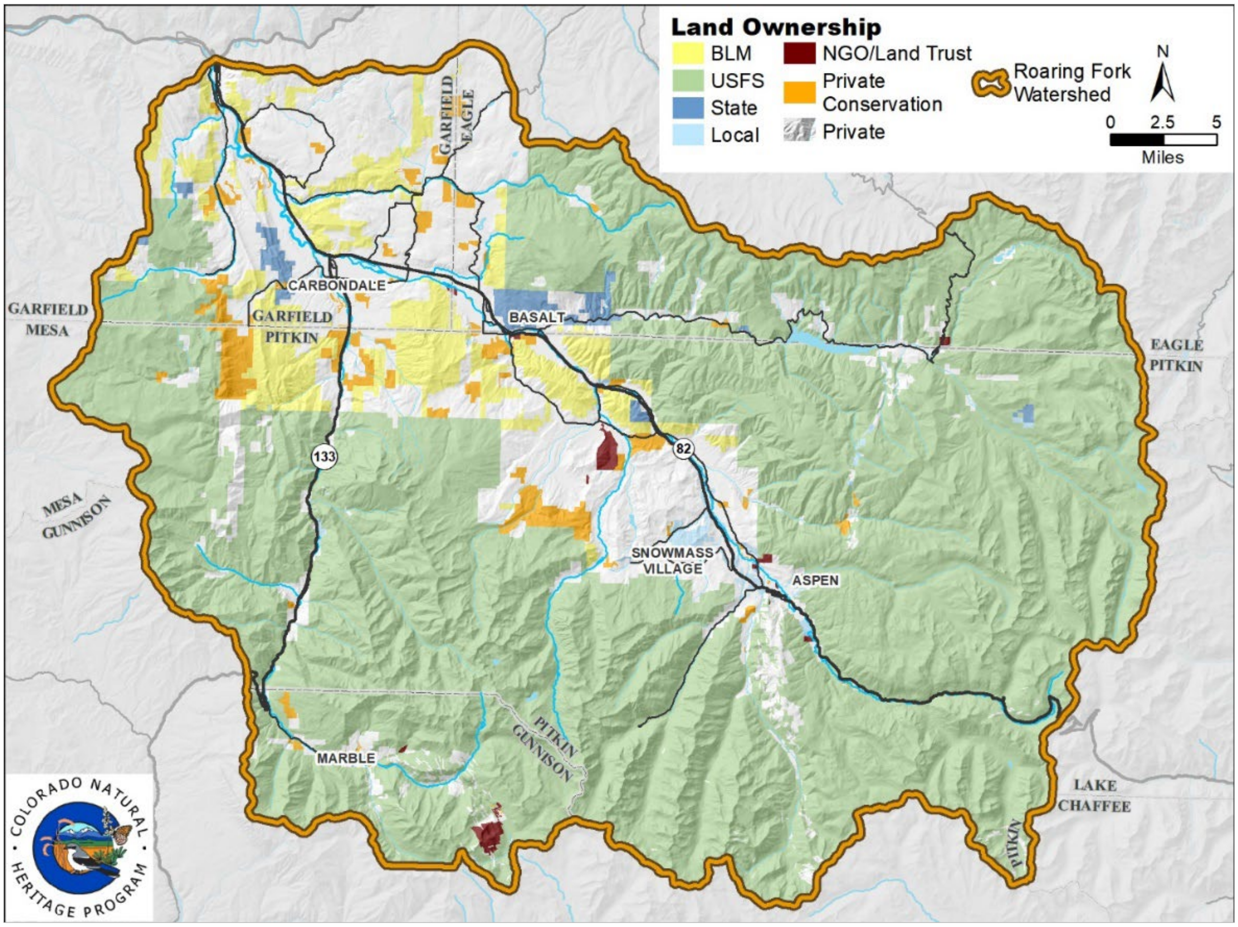

Figure 2. Land ownership in the Roaring Fork Watershed.

Because the Watershed is so large and the interests of the participants were so broad, we determined that the best way to frame the study was through the use of "focal species." Based on consensus of the Science Team and with input from the Stakeholders, the highest priority focal species were defined as **mule deer (*Odocoileus hemionus*)**, **elk (*Cervus elaphus*)**, and **bighorn sheep (*Ovis canadensis*)**[2]. The primary reasons for this decision were widespread concern over declining populations of these iconic animals, and urgency of land-use decisions with potential to affect these species. Also, there was the thought among Project and Science Teams that, by identifying high quality, well-connected areas across the multiple habitat types used by these wide-ranging species, habitats important to many other species would be

[2] There remains considerable interest among members of the Science Team and Stakeholders on species as ecosystem drivers (e.g., beaver, pollinators), species as ecosystem health indicators (e.g., birds), species with potential for human conflict (black bears), and rare species. Due to the practical and logistical realities of time and funding, the Project and Science Teams agreed that the CNHP study would focus on the focal species while WBI would organize local experts and citizen science around beaver, pollinators, birds, and black bears (see Appendix N). CNHP is also conducting a concurrent study of wetland and riparian systems in the Roaring Fork Watershed, funded by the Environmental Protection Agency; data from that effort are incorporated into the Conservation Importance layer. All these efforts, taken together, will greatly improve understanding of the species and habitats across the Watershed. There is continued interest in updated studies of rare species and smaller, less well-known species, including rare plants, bats, amphibians, reptiles, and other taxa. These will hopefully be the focus of future studies.

included as well. We acknowledge that there will still be components of the Watershed's biodiversity that are unaddressed. This gap in the study is filled, in part, by the inclusion of additional existing data layers representing "Conservation Importance" (e.g., areas whose needs may not be adequately captured through a broad-scale habitat management approach), as described in the Watershed Biodiversity and Connectivity Priorities section of this document.

STUDY DESIGN

Goal

Our overarching goal was to develop a science-based set of models and maps to identify areas for the protection and restoration of natural biodiversity and habitat connectivity on a landscape scale.

Objectives

The Project and Science Teams defined the following objectives for the study:

4. Identify high quality habitats for focal species, and places on the landscape that provide connectivity between these locations.
5. Map high priority places where conservation and restoration could enhance landscape function and expand core habitats.
6. Use existing data to combine other significant biodiversity information with focal species data into a watershed-scale conservation and restoration priority map.

Methods

To accomplish our objectives, we designed a study that consisted of field data collected in 2019-2021 and multiple GIS analyses. The key analyses and mapped outputs (models) of the study were 1) **Habitat Quality** for elk, mule deer, and bighorn, and 2) **Conservation Importance**—critical sites for focal species as well as other biodiversity values, culminating in 3) **Conservation and Restoration Priorities** across the landscape. Figure 3 provides a schematic overview of how the steps fit together to create the final decision support map—the Conservation and Restoration Priorities map. A brief description of these steps is provided below. Details on inputs and technical methods are described in Appendices C-M.

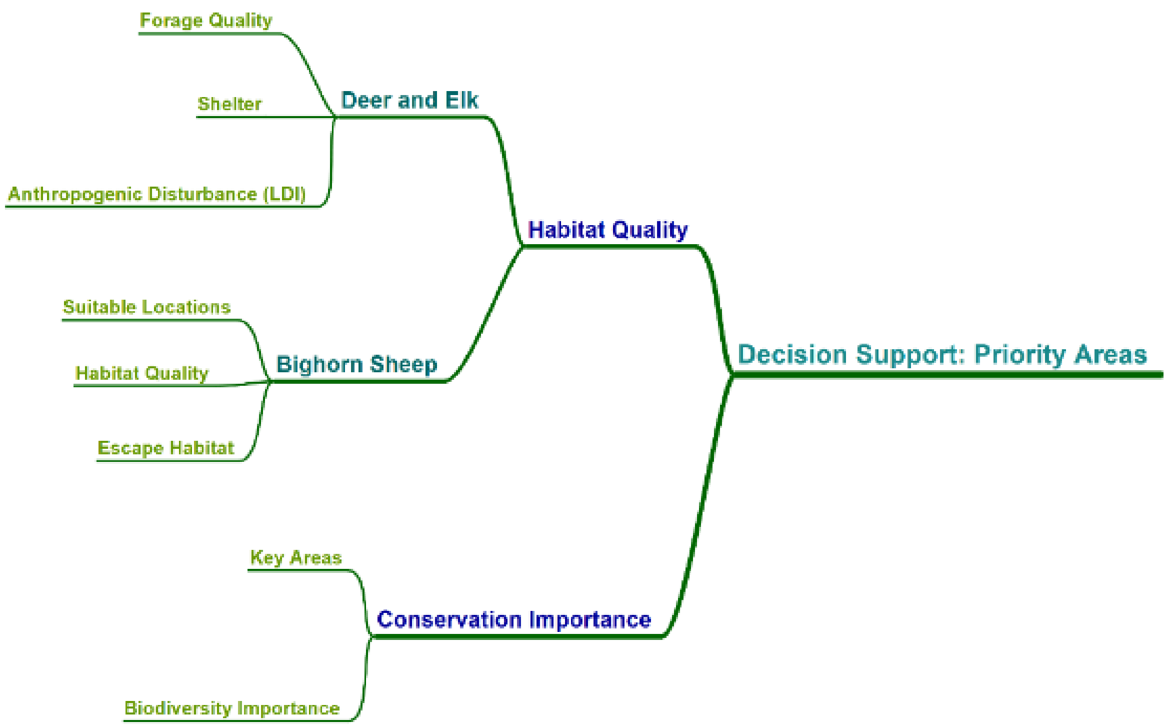

Figure 3. Schematic of overall study design components.

Habitat Quality—Elk and Mule Deer

The basic components of the habitat quality models for elk and mule deer were Forage Quality, Shelter, and Anthropogenic Disturbance (Figure 4).

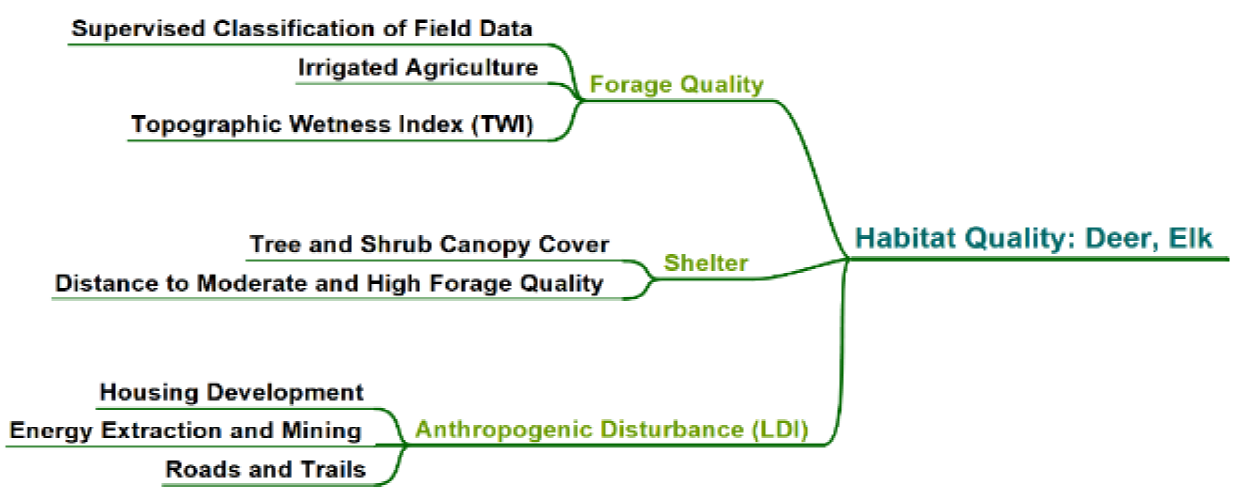

Figure 4. Schematic of inputs for the elk and mule deer habitat quality models.

The steps we took to map habitat quality were:

- Create a forage quality model for elk and mule deer based on field-collected data in natural ecosystems (bighorn were not included in this step because of the availability of an existing habitat model for this species)
- Enhance the forage quality model by incorporating the additional forage contributions of irrigated agricultural fields and the seasonal influences of topographic wetness
- Incorporate the additional habitat components of shelter and anthropogenic disturbance to create a habitat quality model
- Apply a scoring system to the habitat quality models for elk and mule deer to map relative habitat quality (high, moderate, low) across the Watershed
- Modify CPW's existing habitat suitability model for bighorn sheep to map relative habitat quality (high, moderate, low) across the Watershed.

Forage Quality

The nutritional landscape is a critical determinant of wild ungulate population dynamics and ecology, influencing reproductive performance (Roloff 1997), health and survival (Cook et al. 1996, 2004), and migration (McNaughton 1985, Fryxell et al. 1988, Albon and Langvatn 1992, Hebblewhite et al. 2008). The steps we used to develop the forage quality model for elk and mule deer were:

- Field data collection focused on forage resources (2019-2020)
- Scoring of field sampling sites for relative forage quality (high, moderate, low quality)
- Extrapolation of forage quality metrics at sampled sites using satellite imagery classification to model relative forage quality across the remainder of the Watershed
- Final field data collection to validate the forage quality classification model (2021)

Forage quality of natural systems was derived from a combination of plant species diversity, palatability and availability (Figure 5).

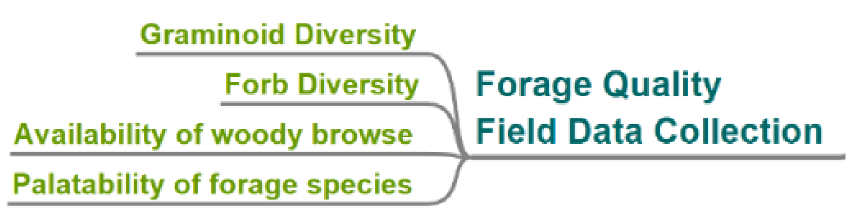

Figure 5. Schematic of field data contribution to the forage quality models.

Field data were collected over two field seasons (2019-2020) for model development, followed by model validation in 2021. At each site, we collected plant cover, height and age class of shrubs and trees, ungulate use (browse intensity and availability) for elk and mule deer. We then classified each site for relative quality of forage using a scoring scale of Low / Moderate / High, using separate rulesets for winter and growing season habitats. We distinguished winter and growing season ranges by mapping average snow persistence over the years 2001-2015, with areas ≥ 70% snow persistence were masked as growing season-only habitat (Hammond et al. 2007). Growing season includes summer as well as the spring and fall shoulder seasons. See Appendix C-G for detailed methods.

Once the initial forage quality model was developed, we applied two modifiers: irrigated agriculture and a measure of moisture on the landscape (Topographic Wetness Index). For irrigated agriculture we assigned a quality score of "Moderate" to all irrigated agricultural fields. The Moderate score reflects the trade-offs between abundant, nutritious forage during limited portions of the year, and the ecological and human conflict costs of prolonged ungulate use of agricultural fields. See Appendix H for details.

There are seasonal differences in the influence of moisture on elk and mule deer habitat. Snow in particular helps dictate the seasonal movements and distribution of ungulates in temperate systems (Montieth et al. 2011, Geremia et al. 2014, Montieth et al. 2018). In winter, drier areas (i.e., less snow) offer better access to forage and reduce the energetic costs associated with moving through deep snow (Parker et al. 1984). During the growing season, wetter areas offer more forage and better nutrition. Therefore, we used a Topographic Wetness Index (TWI) to modify the forage quality models as follows:

- 'Wetter' areas increased the forage quality scores in the growing season model by 1 (i.e., Low -> Moderate, Moderate -> High, High -> Very High).
- 'Drier' areas increased the winter forage quality score by 1.

Shelter

Shelter provides elk and mule deer with both thermal and hiding cover. The distance to shelter from foraging areas is an important attribute for overall habitat quality. Shelter for large ungulates in most natural ecosystems is provided primarily by vegetation (usually trees and shrubs). Dense tree cover and moderately dense shrub cover offer escape cover and thermoregulatory cover, while still allowing animals to move through the forest or shrubland. We used existing vegetation layers to identify areas of high quality forage that are adjacent to good shelter, and weighted those food + shelter complexes higher in scoring habitat quality. See Appendix H for details.

Anthropogenic Disturbance

Human-induced impacts on the landscape can have adverse effects on wildlife and habitats, ranging from eliminating corridors to altering forage quality (e.g., conversion of sagebrush meadows to urban development or crop production) and more. Our Landscape Disturbance Index (LDI) depicts the human footprint on the valley based on mappable infrastructure such as housing development, energy extraction sites and mines, roads, and trails. See Appendix J for details.

Habitat Quality—Bighorn Sheep

The basic components of bighorn sheep habitat quality were **Habitat Suitability** and **Escape Habitat** (Figure 6). One of the key threats facing bighorn sheep herds in Colorado is disease transmission from livestock (especially domestic sheep, but also cattle and goats). Under these conditions, connectivity among herds and habitats is not desirable (George et al. 2009) and was therefore not used as a component of habitat quality.

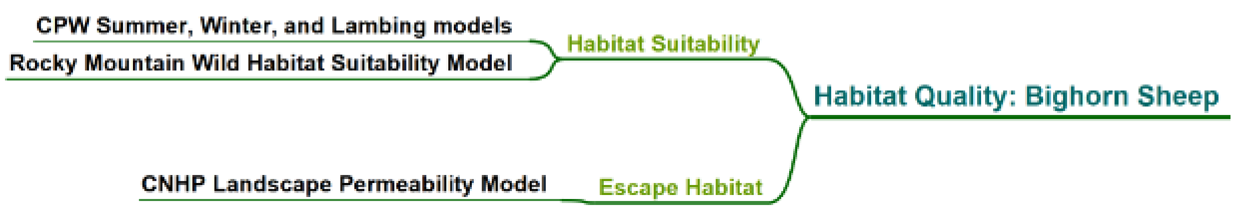

Figure 6. Schematic of inputs for the bighorn sheep habitat quality model.

In 2011, CPW biologists and GIS experts created a deductive habitat suitability model for bighorn sheep, with separate layers for summer, winter, and lambing habitat. This model was developed using animal movement data (telemetry consisting of ground very high frequency (VHF), aerial VHF, satellite, and GPS), slope, terrain ruggedness, canopy cover and vegetation (using LANDFIRE vegetation layer). It synthesizes CPW's accumulated knowledge of bighorn sheep in Colorado. In consultation with CPW and the Science Team, we determined that this existing model was a suitable starting point for the purposes of our study and that additional field effort was not needed. A bighorn sheep Landscape Permeability model was created to identify escape habitat as a part of the habitat quality model, not for identifying movement corridors as was done for elk and mule deer. See Appendix K for details.

Conservation Importance

To complement the habitat quality analyses for the focal species, we added a "Conservation Importance" component which incorporates rare species, small-scale habitats such as wetlands, climate resilient areas, and locally significant natural areas (Figure 7). We created two GIS layers to map Conservation Importance: **Key Areas** and **Biodiversity Importance.**

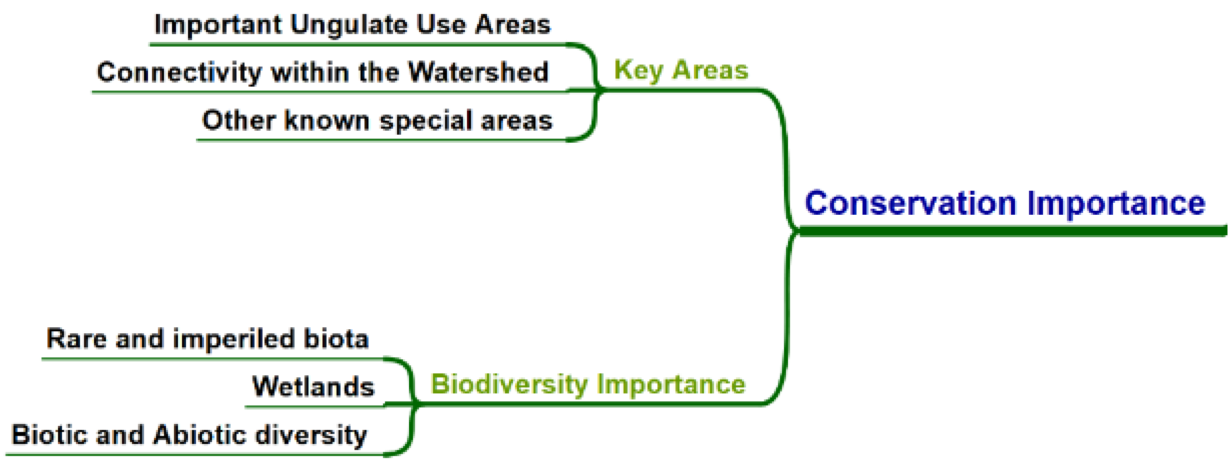

Figure 7. Schematic showing the inputs used to create the Conservation Importance map.

Key Areas

We defined **Key Areas** as relatively small and/or discrete areas that have a critical importance to a functioning natural landscape, including:

- **Important ungulate use areas**—composed of production (birthing) areas, severe winter areas, and winter concentration areas for elk, mule deer, and bighorn according to CPW's Species Activity Maps.
- **Connectivity within the Watershed**—potential local movement corridors for elk and mule deer as well as constraints on that movement based on anthropogenic causes ("pinch points"), plus climate-informed ecological pinch points (places where the landscape inhibits the potential for population movements and range shifts in response to climate change) identified by The Nature Conservancy.
- **Other known special areas—**sites of local significance identified by Science Team members as having known biodiversity value that may not be adequately represented elsewhere. See Appendix L for details.

Biodiversity Importance

We used the concept of **Biodiversity Importance** to incorporate biodiversity values that were unlikely to be captured by analyses centered around our focal species. These biodiversity values include rare and imperiled biota tracked and mapped by CNHP, wetlands, and climate-resilient places identified by The Nature Conservancy (TNC) to highlight areas most likely to be resilient in the face of impacts from climate change (TNC-ECS 2020).

Conservation and Restoration Priority Areas

To create the Conservation and Restoration Priorities map for the Watershed, we combined the habitat quality models for focal ungulates and the Conservation Importance layer (incorporating other biodiversity values in addition to focal ungulates) in a multi-criteria decision process. The decision matrix (Figure 8, Table 1) was applied using each Habitat Quality layer (for the three species and two seasons) separately, resulting in five separate Priority Area layers. These were then combined into a single Priority Areas layer by taking the most significant category present in any one area. Note that the Conservation and Restoration Priorities map and associated decision matrix are not regulatory tools, but rather guides to assist decision-makers and others in prioritizing conservation opportunities.

The resulting map (Results section, Figure 25) highlights areas of high-quality ungulate habitat that also support additional high biodiversity values, as well as areas of degraded ungulate habitat quality that nonetheless have significant conservation importance for other biodiversity values. This map offers a landscape-scale view of opportunities for employing strategies to conserve important, high-quality places and restore degraded habitat in places that still support significant biodiversity values.

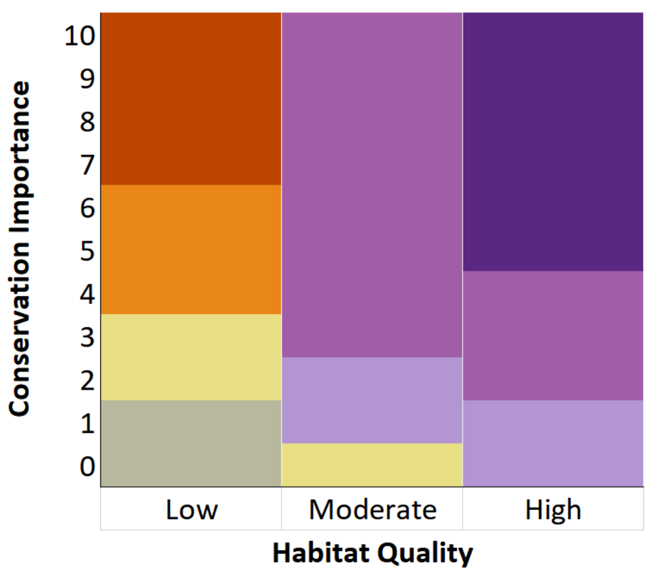

Figure 8. Decision matrix used to combine habitat quality models for focal ungulates with conservation importance to map watershed conservation and restoration priorities.

Table 1. Definitions of categories used on the Conservation and Restoration Priorities map*. *Highest priority for biodiversity = rarest/most imperiled species, wetlands, and/or greatest potential for climate resiliency. †Moderate priority for biodiversity = uncommon but less imperiled species and wetland types, and/or some potential for climate resiliency.*

Matrix Color	Category Name	Definition
	Highest Conservation Value	Places of both highest quality habitat for focal ungulates AND highest priority for biodiversity* - the best of the best; don't lose these.
	High Conservation Value	Places with high or moderate quality habitat for focal ungulates AND moderate priority for biodiversity.†
	Moderate Conservation Value	Places of high or moderate habitat quality for focal ungulates that are generally unfragmented but lacking other biodiversity values. Further investigation of these areas is warranted and maintaining the ecological integrity of these areas may benefit the Watershed as a whole.
	Lower Conservation Value	Places with lower quality habitat for focal ungulates and fewer biodiversity values documented; often in proximity to developed areas. These areas may not warrant direct conservation or restoration action; additional information is needed.
	Most Significant Restoration Opportunity	Places of lower habitat quality for focal ungulates but very high conservation importance for other biodiversity values. These areas would strongly benefit from protection from further degradation or loss, as well as restoration of natural processes where applicable.
	Significant Restoration Opportunity	Places that are important for biodiversity but improvements in habitat quality/connectivity are likely needed for focal ungulates. Protecting and/or restoring these areas would benefit the ecological integrity of the Watershed as a whole.
	Developed or Severely Impacted	Not practical conservation or restoration opportunities due to the dominance of urban or other developed areas and established transportation networks. Due to the nature of the input data used, areas of bare rock, perennial ice, or other naturally unvegetated sites may be mapped in this category.

RESULTS AND DISCUSSION

Forage Quality – Elk and Mule Deer

The Roaring Fork Watershed represents a diverse array of ecological systems[3] tied to climate, elevation, slope, geology, soils, and other characteristics of the surrounding landscape. In total, 129 field sites were sampled during the summers of 2019 and 2020 across 11 ecological systems; an additional 102 sites were visited during field validation of the forage quality model, for a total of 231 distinct sites visited over the life of the study (Figure 9, Table 2). The COVID-19 pandemic severely limited our field crews so the number of sites sampled was lower than planned. Nevertheless, we have confidence in the final forage quality models. The supervised classification methods used to scale the field data to the larger Watershed are robust against smaller sample sizes and the results have been extensively reviewed and accepted by multiple local partners who know the Watershed well.

Figures 10-12 illustrate site-specific examples of ecological systems from across the Watershed that scored low, moderate, and high for forage quality based on either winter or growing season scoring metrics. Field biologists observed during their field assessments that the abundance, availability, and diversity of palatable, highly digestible forage for elk and mule deer was relatively consistent within a given ecological system, though notable exceptions exist at some sites. For instance, regular, intensive grazing at some sites reduced forage quality and availability in Aspen communities, which otherwise provided moderate to high quality forage in most locations throughout the Watershed. Edaphic and other natural conditions related to the ecology of a given site or ecological system can also drive the abundance and nutritional quality of available forage. For example, rocky Pinyon-Juniper woodlands receiving intense south-facing solar exposure produced a scant amount of palatable winter or growing season forage. Similarly, open-canopied Spruce-Fir forest interspersed with wet meadows and other subalpine vegetation typically provided an abundance of high quality growing season forage, whereas closed-canopy Spruce-Fir forests typically did not. Note that both moderate and high quality categories provide elk and mule deer with excellent opportunities to meet their caloric needs, and the distinction between these categories may not be as important as the distinction between moderate and low quality categories.

Figures 13 and 14 show the final forage quality models for winter and growing season, respectively. Note that there is overlap in area between the higher elevations of our modeled winter habitat and the lower elevations of our modeled growing season habitats. This is to be expected given the nature of ecotonal habitats where winter and growing seasons intergrade. Also, this overlapping area could reflect valuable transition habitat during shoulder seasons, as well as opportunity for animal behavioral responses to changing climate conditions.

[3] We use the term "ecological system" here to reflect major plant communities or habitat types that most members of a lay audience would recognize on the landscape. Ecological systems were mapped using the Southwest Regional GAP data layer (https://swregap.org/). See Appendix M for more information on how we combined land cover categories from the land cover layer into ecological systems.

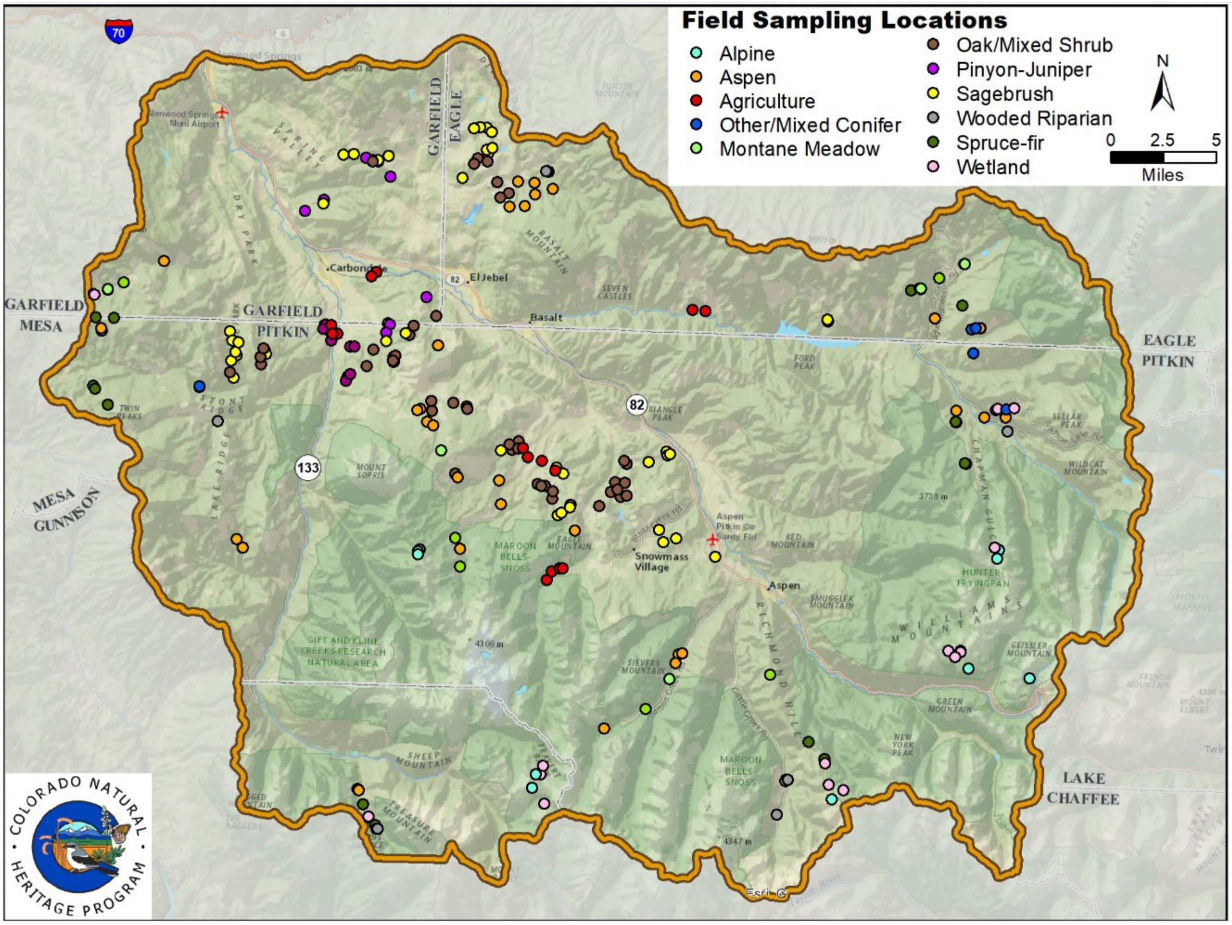

Figure 9. Distribution of all sites sampled during 2019-2021 field seasons, by ecological system type.

Table 2. Number of points sampled during the 2019-2021 field seasons and the size of each ecological system. *Note that the acreages of each system are derived from the land cover layer used in the study and so are only approximations.*

Ecological System	Number of field points	Total Acreage in Watershed
Alpine	10	46,126
Aspen	37	153,432
Oak/Mixed Shrub	49	104,538
Pinyon-Juniper	16	42,802
Sagebrush	40	68,149
Spruce-Fir	15	263,887
Other/Mixed Conifer	7	59,232
Wooded Riparian	8	43,666
Wetland	18	23,109
Montane Meadow	15	20,952
Agriculture	16	30,355
Total	231	856,247

Figure 10. Photos A-F represent sites across the Watershed, within both winter and growing season ranges that scored low for forage quality. *Although scoring rules differed for winter vs. growing season, all sites pictured had low diversity and availability of palatable forbs, graminoids, and trees and shrubs. In many cases, especially for the winter range sites, understory diversity was suppressed by the presence of nonnative invasive plants like cheatgrass* (Bromus tectorum) *(photo D) and* Sisymbrium altissimum *(photo F), or due to regular, intensive grazing (photo C). Edaphic and other natural conditions related to the ecology of a given site or community (slope, exposure, etc.) can also drive the abundance and nutritional quality of available forage, e.g., alpine tundra (photo A), dense spruce-fir forest (photo B), and rocky Pinyon-juniper woodland (photo E).*

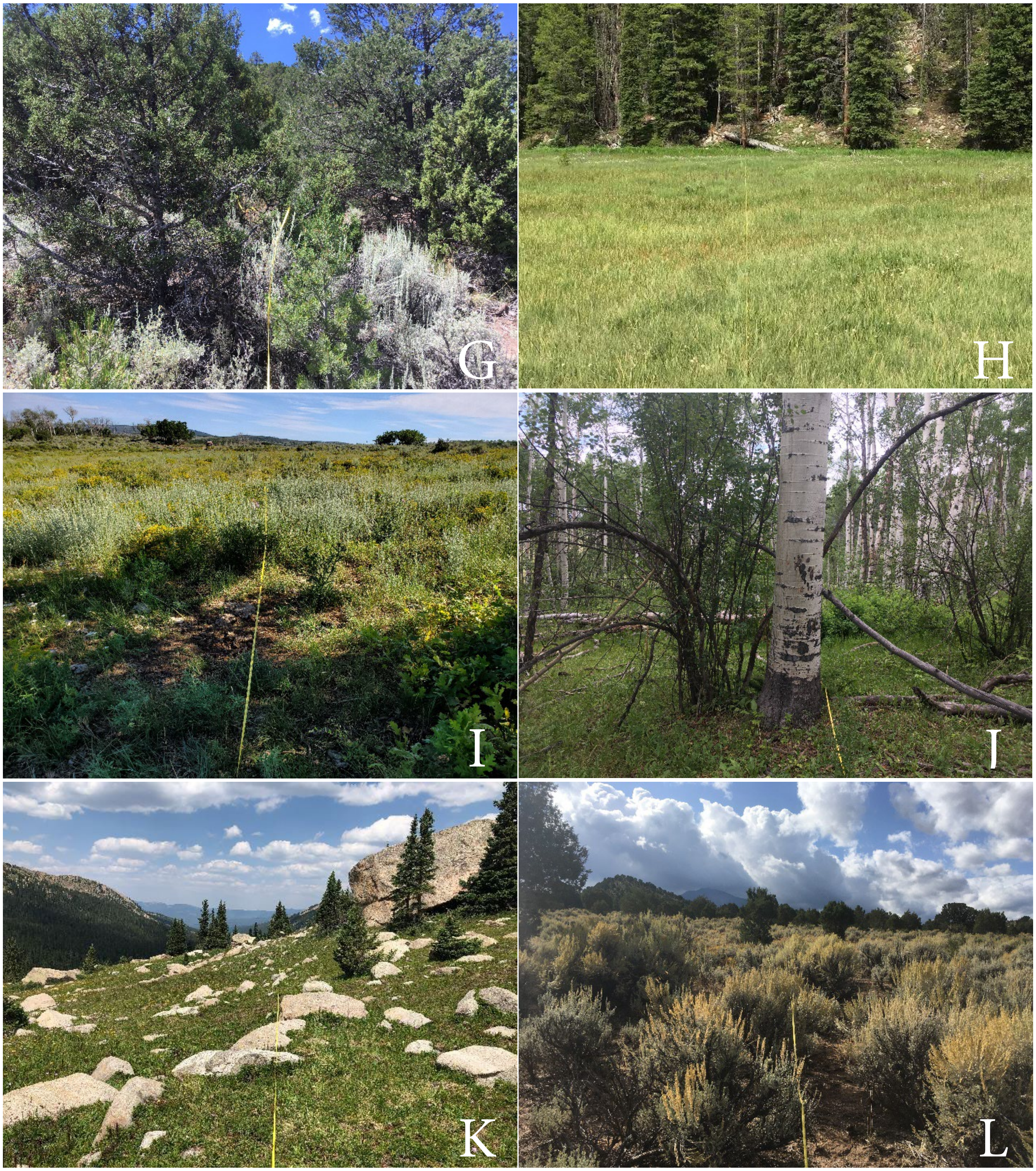

Figure 11. Photos G-L represent sites across the Watershed, within both winter and growing season ranges that scored moderate for forage quality. *Although scoring rules differed for winter vs. growing season, all sites pictured had good relative diversity and availability of palatable forbs, graminoids, and trees and shrubs. Diversity and abundance might be reduced by the presence of low to moderate grazing intensities or invasive species, but impacts were moderate to negligible (photo I, J, and L). Edaphic and other natural conditions help drive the abundance and nutritional quality of available forage in moderate forage quality sites too, but these communities are not facing the extreme limitations or stressors (e.g., water scarcity, thin to absent soils, intense sun and wind exposures, excessive shade) characteristic of communities represented in photos A, B, and E.*

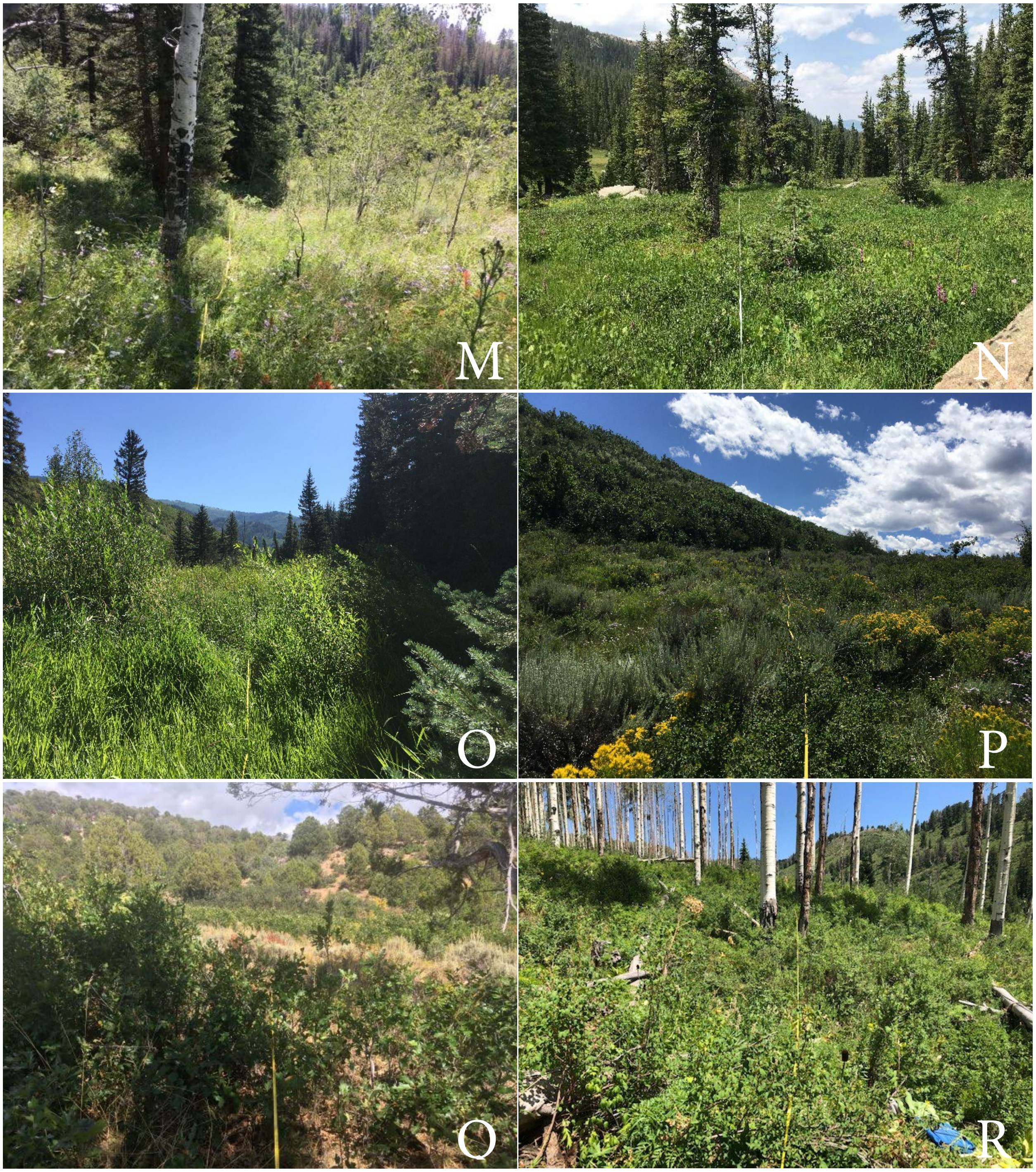

***Figure 12. Photos M-R represent sites across the Watershed, within both winter and growing season ranges that scored high for forage quality**. Although scoring rules differed for winter vs. growing season, all sites pictured had excellent relative diversity and availability of palatable forbs, graminoids, and trees and shrubs. Even in the presence of light to moderate grazing intensities, these were species rich communities (photos Q and R). Edaphic and other natural conditions help drive the abundance and nutritional quality of available forage in these high quality sites, several of which were in close proximity to, or matrixed within larger wetland complexes, e.g., spruce-fir, wet meadow (photo N), and mixed-conifer, willow-shrub riparian zone (photo O).*

Winter

For the winter season, the following discussion addresses two scales: our modeled winter habitat and known winter distribution of elk and mule deer based on CPW's Species Activity Maps (SAM[4]). CPW SAM maps reflect on-the-ground knowledge of CPW field staff and annual herd census, in addition to research study results when available; thus, they represent our best understanding of where elk and mule deer populations occur seasonally across the Watershed.

The areal extent of our modeled winter range (~530,000 acres) extends beyond that represented in the CPW SAM for both elk and mule deer (<300,000 acres). We used snow persistence averaged over the years 2001-2015 to delineate the full extent of potential winter habitat, rather than limiting it to known occupied range represented by SAM. Climate change leading to atmospheric warming and the loss and/or truncated periods of snow cover will presumably lead to elk and mule deer utilizing higher elevation habitats for greater portions of the year. Anecdotal observations have noted delays in the typical timing of elk and mule deer moving from high elevation summer and transitional habitat down to lower elevation winter range following a warm and dry fall and early-winter like that experienced in late 2021 (pers. comm. John Groves, CPW 2021).

Because both current distribution and potential future distribution are important to consider in habitat management, we discuss our forage quality results for both the larger modeled winter range as well as the areas currently delimited on SAM maps for the winter season. A similar comparison for growing season isn't supported by the SAM maps. Winter season is when animals congregate in larger groups and habitat use can be more accurately and consistently delineated, which is not the case during the growing season.

[4] See Appendix B and CPW's website for additional information on SAM https://cpw.state.co.us/learn/Pages/KMZ-Maps.aspx and https://cpw.state.co.us/learn/Maps/CPW-Public-GIS-Species-Activities-Definitions.pdf#search=species%20activity%20map%20definitions.

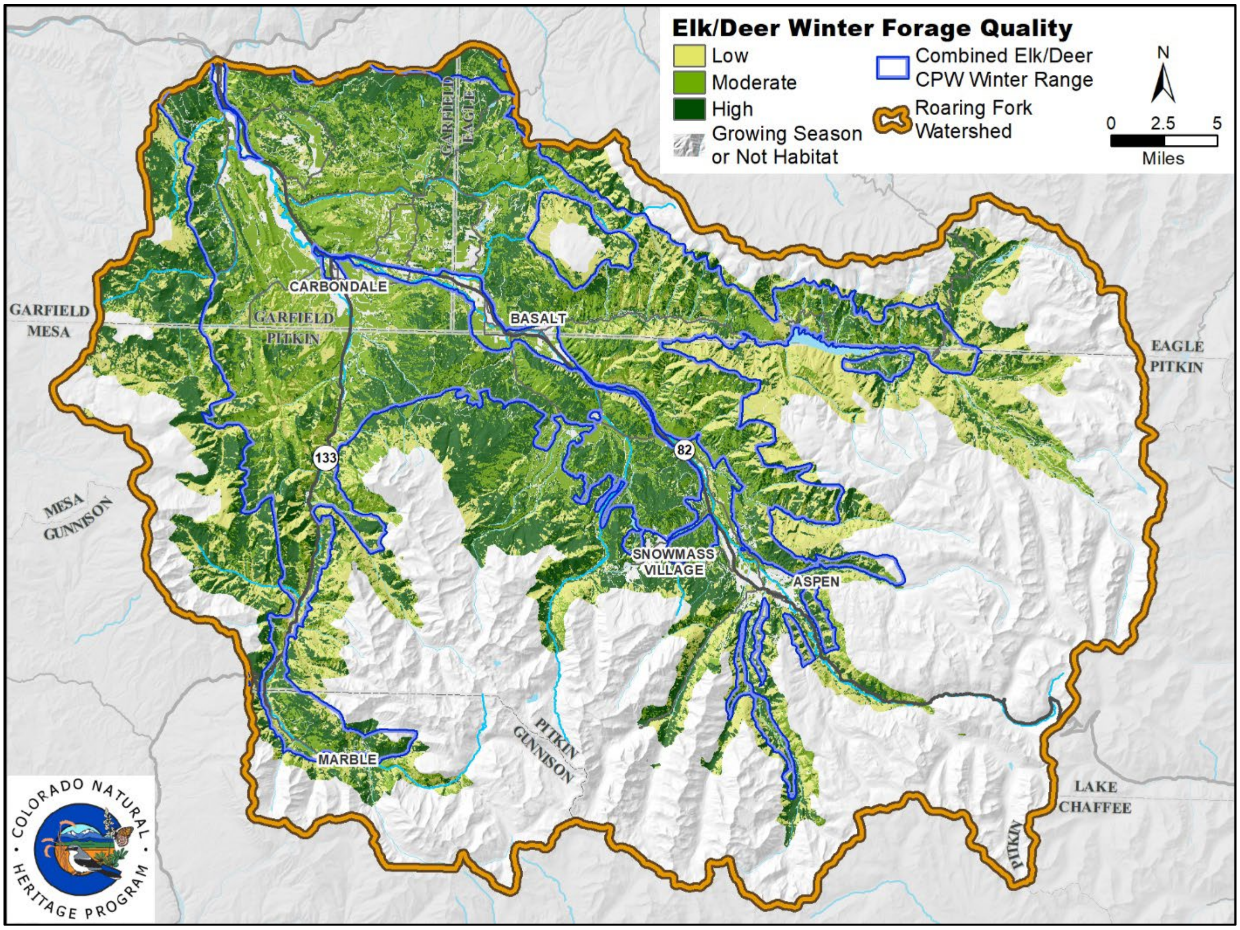

Figure 13. Relative forage quality for elk and mule deer across modeled winter range, plus the extent of CPW SAM winter ranges (combined) for elk and mule deer.

Modeled Winter Range

Considering all ecological systems together, 70% of the modeled winter range has high or moderate quality forage (Table 3). With the exception of Spruce-Fir, all of the ecological systems that make up the majority of *modeled* winter range offer predominantly high to moderate quality forage resources according to our models. The Aspen ecological system makes up the largest portion of modeled winter range, followed by Oak/Mixed Shrub, Spruce-Fir, and Sagebrush. Across Aspen communities, almost 70% offers high quality forage. Including both high and moderate quality categories, that percentage rises to 82%. Over half (57%) of the Oak/Mixed Shrub communities within modeled winter range offer high quality forage; adding high and moderate quality forage within Oak/Mixed Shrub raises that percentage to 92%. Approximately half of the Sagebrush within modeled winter range is comprised of high quality forage (51%); adding high and moderate quality categories together brings that percentage up to 86%. For Spruce-Fir, that pattern is different: only 6% in high quality and 23% for high plus moderate quality.

***Table 3. Proportion of each ecological system within* modeled winter range *for elk and mule deer represented by high, moderate, and low quality* forage.** *There may be slight discrepancies due to rounding. *The total area of the modeled winter range includes other land covers not included here, such as golf courses and lawns, which have theoretical forage value, and others such as built-up areas, bare rock and open water which are not forage.*

Ecological System	Low Quality	Moderate Quality	High Quality	Total System Acres[5]	% of Modeled Winter Range
Alpine	15%	60%	25%	59	<1%
Aspen	18%	13%	69%	132,218	25%
Oak/Mixed Shrub	8%	35%	57%	94,764	18%
Pinyon-Juniper	13%	72%	14%	37,878	7%
Sagebrush	14%	35%	51%	60,750	11%
Spruce-Fir	77%	17%	6%	70,490	13%
Other/Mixed Conifer	73%	20%	7%	50,142	9%
Wooded Riparian	26%	25%	49%	5,945	1%
Wetland	8%	24%	68%	3,796	1%
Montane Meadow	7%	31%	62%	7,590	1%
Agriculture	24%	18%	57%	3,938	1%
All Systems by Quality	30%	27%	43%	467,510	88%*

Known Winter Range

All of the ecological systems that make up the majority of *known* winter range offer predominantly high to moderate quality forage resources according to our models (Table 4). The Oak/Mixed Shrub ecological system makes up the largest portion of known winter range, followed by Sagebrush, Aspen, and Pinyon-Juniper. Across Oak/Mixed Shrub communities, approximately 56% offers high quality forage. Including both high and moderate quality categories, that percentage rises to 93%. Almost half of the Sagebrush system (49%) has high quality forage; adding moderate quality brings that total to 85%. Over half (65%) of the Aspen communities within known winter range offer high quality forage; adding high and moderate quality categories together raise that total to 83%. The majority of Pinyon-Juniper within winter range is comprised of moderate quality forage (73%); high quality forage in this system is much less common (11%). The lower percentage of high quality forage within Pinyon-Juniper systems is not surprising; Pinyon-Juniper may be naturally sparsely vegetated with some stands having few palatable species in the understory. However, many stands still offer some forage and provide important shelter. Note also that Pinyon-Juniper offers crucial resources for many other species, especially birds.

[5] Acreages in Tables 3 – 5 calculated from the overlap of SWReGAP land cover with the forage quality models, which was simplified from the original ecological system descriptions; only acreages from natural vegetated land cover classes (plus agriculture) that overlap the forage quality classes are shown in the table. Due to differences in methodology, time period, and purpose, the overlap between vegetated land cover from SWReGAP and areas designated as forage in the forage quality models is not exact and the relative percentages in the tables are more pertinent than the reported acreages. Irrigated agricultural lands are included on Figures 13 and 14 for illustrative purposes; acres are in Tables 6-8. See Appendices C and H for technical methods.

*Table 4. **Proportion of each ecological system within*** **known winter range** ***based on SAM for elk and mule deer represented by high, moderate, and low quality*** **forage**. *There may be slight discrepancies due to rounding. *The total area of the known winter range includes other land covers not included here, such as golf courses and lawns, which have theoretical forage value, and others such as built-up areas, bare rock and open water which are not forage.*

Ecological System	Low Quality	Moderate Quality	High Quality	Total System Acres[6]	% of CPW Winter Range
Aspen	17%	18%	65%	49,104	17%
Oak/Mixed Shrub	7%	37%	56%	78,110	27%
Pinyon-Juniper	13%	73%	14%	37,089	13%
Sagebrush	15%	36%	49%	47,975	16%
Spruce-Fir	69%	19%	13%	12,330	4%
Other/Mixed Conifer	71%	23%	6%	20,734	7%
Wooded Riparian	26%	33%	42%	2,086	1%
Wetland	5%	32%	62%	969	<1%
Montane Meadow	6%	48%	46%	2,458	1%
Agriculture	25%	19%	56%	2,945	1%
All Systems by Quality	20%	36%	44%	253,799	86%*

Growing Season

Across all ecological systems within growing season range, 76% falls within the high quality category for forage (Table 5). Spruce-Fir and Aspen ecosystems occupy the most area within the growing season range, at 37% and 16% respectively, followed by Other/Mixed Conifer, Wooded Riparian, and Alpine, each at approximately 5-6%. Across the Spruce-Fir system, 74% offers high quality forage (77% for high and moderate quality combined). Prior to our field investigations, this result would have been surprising given the common assumption that Spruce-Fir stands are often too dense and shady to support significant understory grasses and forbs. However, several field sites surveyed within Spruce-Fir systems in the growing season range exhibited open-canopy forests surrounding dense, highly palatable and nutritious forage within wet to mesic subalpine meadows. Seventy-eight percent of the Aspen communities within growing season range offer high quality forage according to our model. This number rises to 99% considering high and moderate quality categories together. This pattern holds true for the next largest ecological system across growing season range, Other/Mixed Conifer (79% and 93%, respectively). Within the Alpine system, 66% was modeled as high quality forage, or 76% including the moderate quality category. Though Wooded Riparian and Wetland systems occupy a smaller proportion of the growing season range (~3% each), they offer critically important resources during this season. Those systems combined are comprised of ~80-90% high quality forage (~96% high and moderate quality combined).

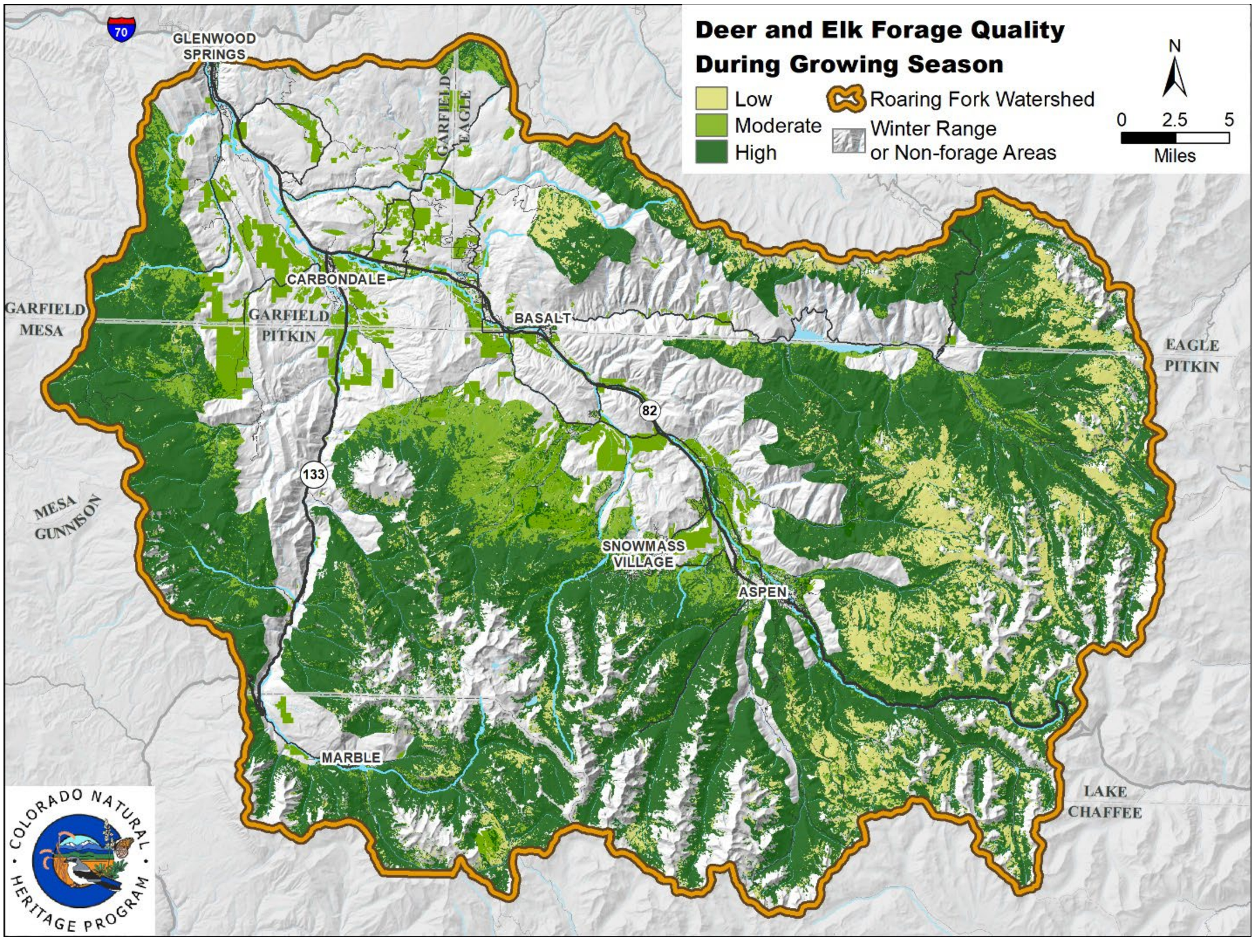

Figure 14. Relative forage quality for elk and mule deer across modeled growing season habitat. Note that elk and mule deer may occasionally use areas depicted on the map as winter range during growing season months.

***Table 5. Proportion of each ecological system within elk and mule deer* growing season *range represented by high, moderate, and low Quality* forage**. *There may be slight discrepancies due to rounding. *The total area of the growing season range includes other land covers not included here, such as built-up areas, bare rock and open water which are not forage.*

Ecological System	Low Quality	Moderate Quality	High Quality	Total System Acres[6]	% of Growing Season Range
Alpine	24%	10%	66%	26,017	4%
Aspen	1%	21%	78%	101,132	16%
Oak/Mixed Shrub	2%	47%	50%	18,503	3%
Pinyon-Juniper	3%	19%	78%	1,023	0.2%
Sagebrush	7%	43%	50%	13,531	2%
Spruce-Fir	23%	3%	74%	234,337	37%
Other/Mixed Conifer	7%	14%	79%	37,419	6%
Wooded Riparian	5%	5%	91%	37,440	6%

Ecological System	Low Quality	Moderate Quality	High Quality	Total System Acres[6]	% of Growing Season Range
Wetland	4%	7%	89%	19,114	3%
Montane Meadow	9%	12%	79%	16,902	3%
Agriculture	4%	38%	58%	2,557	0.4%
All Systems by Quality	13%	11%	76%	**481,959**	**76%***

Habitat Quality – Elk and Mule Deer

The forage quality models represent our best understanding of the nutritional landscape available for elk and mule deer in the Roaring Fork Watershed. Building off of the forage quality models, the habitat quality models represent a suite of seasonally defined needs and pressures, including shelter, connectivity, and anthropogenic disturbance in addition to forage. Consequently, the habitat quality models and analyses focus more heavily on human-related impacts and differences in habitat quality relative to public vs. private land ownership. We developed one habitat quality model for winter for both elk and mule deer combined (Figure 15) because the ranges and habitats used by these species have extensive overlap during this time of year. For the growing season, we developed separate habitat quality models for elk (Figure 18) and mule deer (Figure 19) to better reflect different habitat preferences between the species when access to habitats is not as restricted, and more choice is readily available.

Although approximately 70-80% of modeled winter range, known winter range, and growing season range were found to have moderate to high quality *forage* for both elk and mule deer, the benefit of nutritional forage is lessened when accounting for availability of shelter and the impacts from anthropogenic disturbance.

Winter

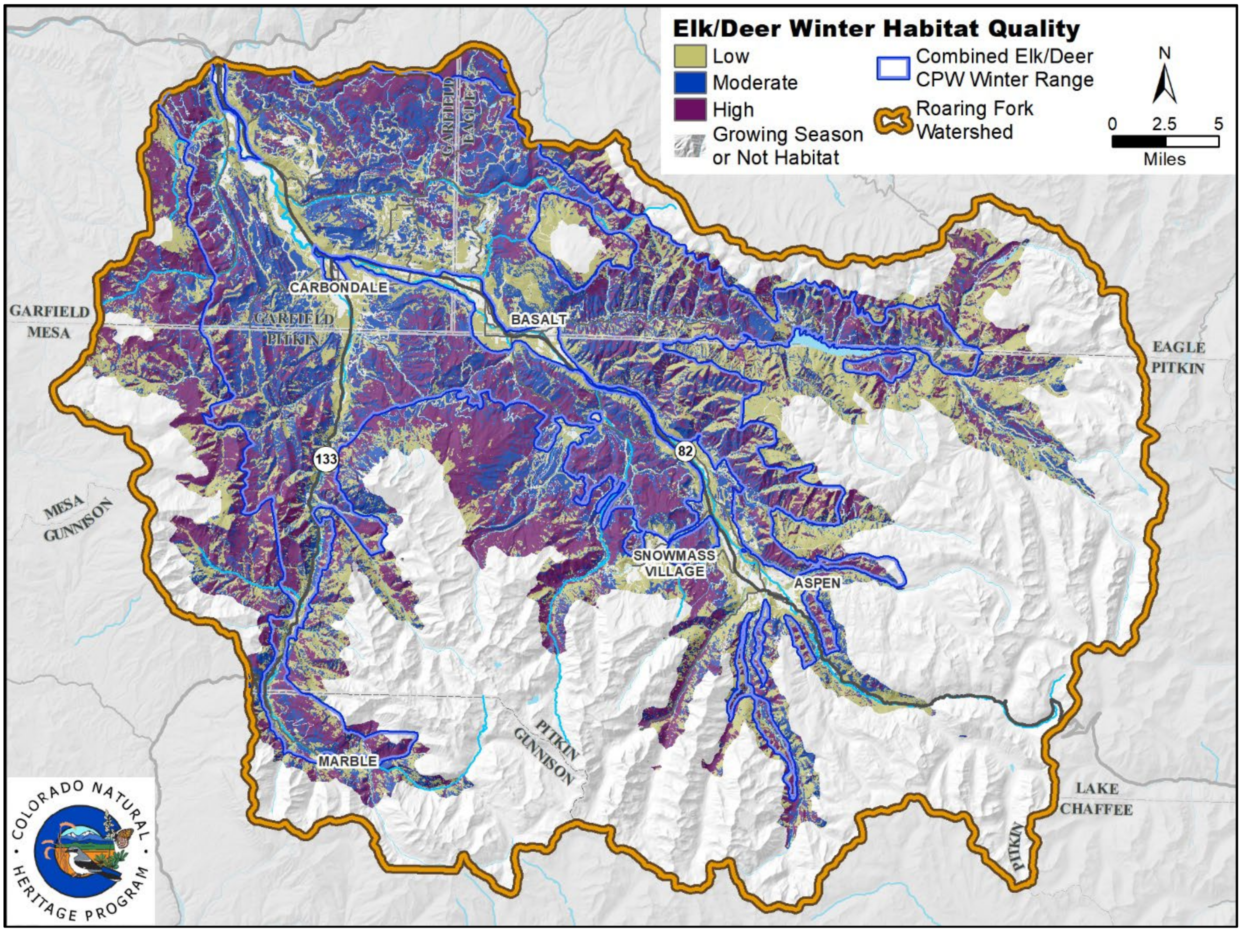

Figure 15. Relative habitat quality for elk and mule deer across **modeled** *winter range, plus the extent of CPW SAM winter ranges (combined) for elk and mule deer.*

Modeled Winter Range

Considering all ecological systems across the modeled winter range, approximately 64% is in either the high or moderate category for habitat quality (Table 6, Figure 16). That number was approximately 70% in the forage quality model, so there was some reduction in quality overall when the additional habitat quality metrics were incorporated. This is an absolute reduction of 7%, which translates into a roughly 9% loss of area from the high or moderate quality categories once the additional habitat quality metrics were incorporated (6 divided by 70). For the largest systems within modeled winter range (Aspen and Oak/Mixed Shrub), the majority of each system is still in the high or moderate quality categories for habitat at 81%. The Sagebrush system is also among the most important winter habitats due to the important woody browse it provides. Across the Sagebrush in modeled winter range, approximately three-quarters (73%) is moderate or high quality habitat.

One important point about the modeled winter range compared to the known winter range is the greater Aspen component. Aspen makes up about 25% of the modeled winter range compared to 17% of the known winter range (Tables 6 and 7). As climate change progresses, the Aspen stands in these transition zones will be important places to pay attention to. As winters get warmer and snowpack is reduced, we expect elk and mule deer to use those areas more and more, especially in the shoulder seasons.

***Table 6. Proportion of each ecological system within* modeled winter range *for elk and mule deer represented by high, moderate, and low quality* habitat.** *Values are rounded to nearest whole number, there may be slight discrepancies due to rounding. *The total area of the modeled winter range includes other land covers not included here, such as golf courses and lawns, built-up areas, bare rock, and water, which are not habitat.*

Ecological System	Low Quality	Moderate Quality	High Quality	Total System Acres[6]	% of Modeled Winter Range
Alpine	10%	50%	41%	59	<1%
Aspen	20%	19%	62%	134,217	25%
Oak/Mixed Shrub	19%	37%	44%	101,198	19%
Pinyon-Juniper	42%	47%	11%	39,965	8%
Sagebrush	27%	38%	36%	64,706	12%
Spruce-Fir	73%	19%	8%	70,944	13%
Other/Mixed Conifer	70%	21%	9%	50,122	9%
Wooded Riparian	43%	25%	32%	6,425	1%
Wetland	10%	28%	61%	3,883	1%
Montane Meadow	10%	34%	55%	7,715	1%
Agriculture	56%	38%	6%	24,446	5%
All Systems by Quality	37%	29%	35%	503,623	95%*

[6] Acreages for Tables 6 – 9 are calculated from the overlap of SWReGAP land cover with the habitat quality models. The land cover layer was simplified from the original ecological system descriptions, and only acreages from natural vegetated land cover classes (plus agriculture) that overlap the forage quality classes are shown in the table. Due to differences in methodology, time period, and purpose, the overlap between vegetated land cover from SWReGAP and areas designated as habitat in the habitat quality models is not exact and the relative percentages in the tables are more pertinent than the reported acreages. See Appendix H for technical methods.

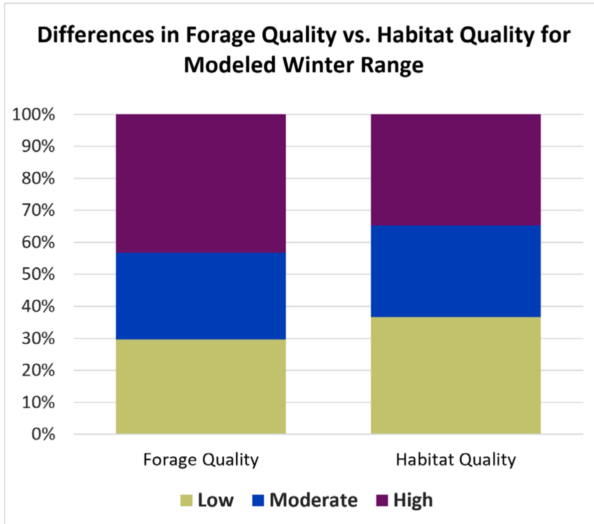

Figure 16. Comparison of forage quality and habitat quality for modeled *winter range.*

Known Winter Range

Considering all ecological systems across the known winter range, 69% is in either the high or moderate category for habitat quality (Table 7, Figure 17). That number was approximately 80% in the forage quality model, so there was some reduction in quality overall when the additional habitat quality metrics were incorporated. This is an absolute reduction of 11%, which translates into a roughly 14% loss of area from the high or moderate quality categories once the additional habitat quality metrics were incorporated (11 divided by 80). The largest systems within known winter range—Oak/Mixed Shrub, Sagebrush, and Aspen—together comprise approximately 62% of the undisturbed portion of the range. The majority of each system is still in the high or moderate quality categories for habitat at 83%, 73%, and 82%, respectively. Other important systems within the known winter range are Pinyon-Juniper, which provides important cover (stands that contain mountain mahogany, bitterbrush, and serviceberry) also provide important forage), and agricultural fields which are heavily used this time of year. For each of these systems, only a minority of the area is high quality habitat according to our model. However, areas within the moderate quality category (48% of Pinyon-Juniper, 41% of Agriculture) are important components of the known winter range.

Table 7. Proportion of each ecological system within **known winter range** *for elk and mule deer represented by high, moderate, and low quality* **habitat.** *There may be slight discrepancies due to rounding. *The total area of the modeled winter range includes other land covers not included here, such as golf courses and lawns, built-up areas, bare rock, and open water, which are not habitat.*

Ecological System	Low Quality	Moderate Quality	High Quality	Total System Acres[7]	% of CPW Winter Range
Aspen	18%	22%	60%	49,873	17%
Oak/Mixed Shrub	17%	38%	45%	82,543	28%
Pinyon-Juniper	41%	48%	11%	39,007	13%
Sagebrush	27%	39%	34%	51,237	17%
Spruce-Fir	66%	23%	11%	12,786	4%
Other/Mixed Conifer	66%	23%	10%	20,776	7%
Wooded Riparian	50%	30%	20%	2,493	1%
Wetland	9%	32%	59%	994	<1%
Montane Meadow	9%	45%	45%	2,509	1%
Agriculture	54%	41%	5%	17,868	6%
All Systems by Quality	31%	35%	34%	280,085	95%*

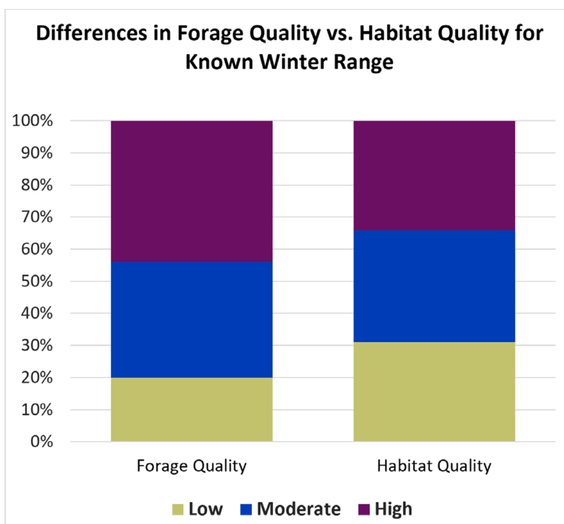

Figure 17. Comparison of forage quality and habitat quality for **known** *winter range.*

Growing Season – Elk

Considering all ecological systems across the growing season range, approximately 74% is in either the high or moderate category for habitat quality for elk (Table 8, Figure 20). That number was approximately 87% in the forage quality model, so there was some reduction in quality overall when the additional habitat quality metrics were incorporated. This is an absolute reduction of 13%, which translates into a roughly 15% loss of area from the high or moderate quality categories once the additional habitat quality metrics were incorporated (13 divided by 87). For the largest systems within growing season range for elk (Spruce-Fir and Aspen), the majority of each system is still in the high or moderate quality categories for habitat at 75% and 87%, respectively. Though Alpine, Wetlands and Wooded Riparian cover a relatively minor proportion of the total area within the growing season range, these systems make important contributions. In particular, we consistently observed that the wetlands in the ecotone between subalpine (especially Spruce-Fir) and Alpine throughout the Watershed were very heavily used by elk and mule deer. As with the larger systems, most of the Alpine, Wetlands, and Wooded Riparian are high or moderate quality habitat (77%, 94%, and 77%, respectively). Note that Wetlands and Wooded Riparian together make up approximately 9% of the growing season range. Compared to the state of Colorado, where wetlands occupy approximately 2% of the land area, this is a wet basin.

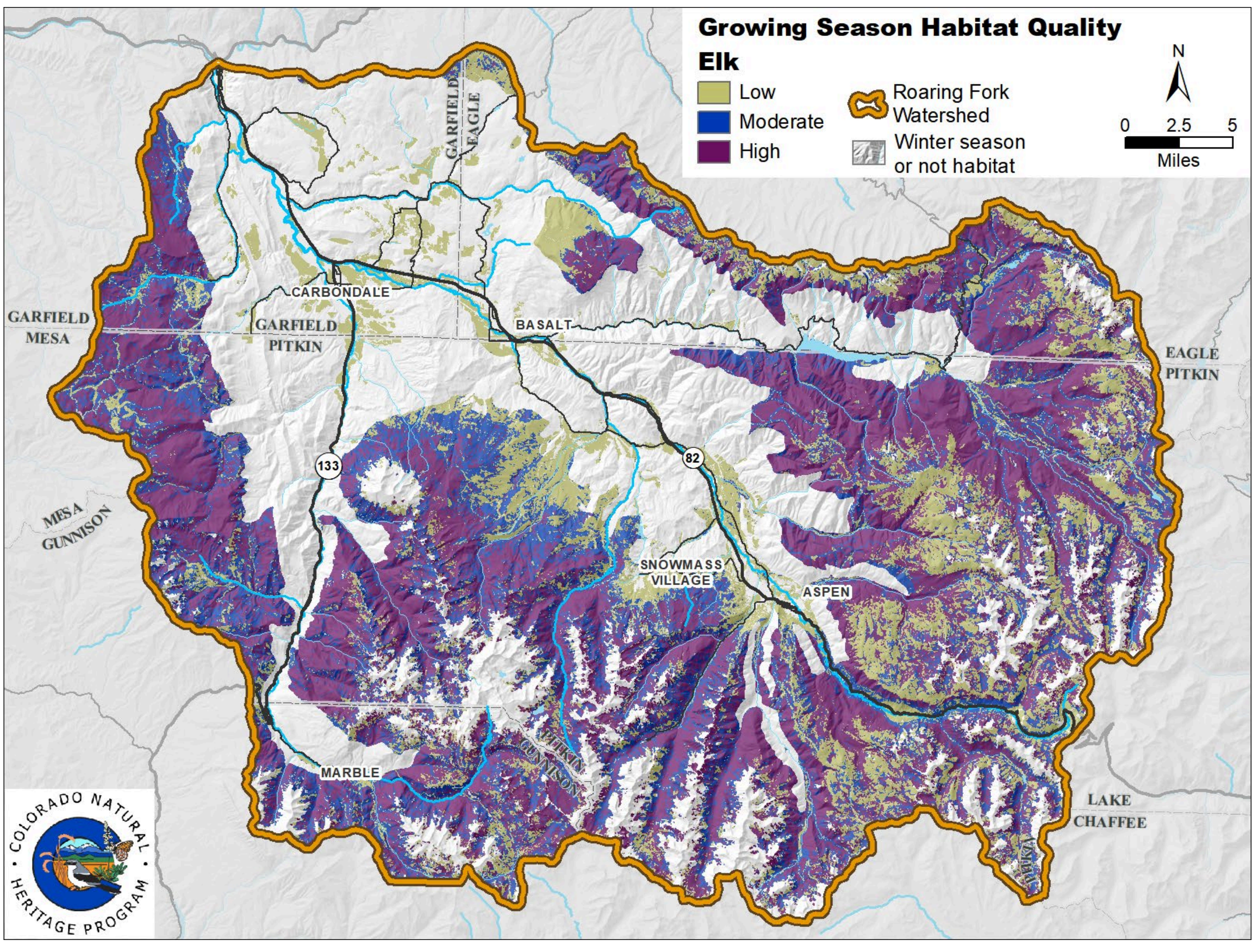

Figure 18. Relative habitat quality for elk during growing season.

***Table 8. Proportion of each ecological system within* growing season *range for* elk *represented by high, moderate, and low quality* habitat.** *There may be slight discrepancies due to rounding. *The total area of the growing season range includes other land covers not included here, such as golf courses and lawns, built-up areas, bare rock, and open water, which are not habitat.*

Ecological System	Low Quality	Moderate Quality	High Quality	Total System Acres[7]	% of Growing Season Range
Alpine	23%	12%	65%	33,900	5%
Aspen	12%	37%	50%	101,923	16%
Oak/Mixed Shrub	55%	34%	11%	20,062	3%
Pinyon-Juniper	83%	13%	4%	1,425	0.2%
Sagebrush	69%	26%	5%	14,907	2%
Spruce-Fir	25%	19%	56%	242,799	38%
Other/Mixed Conifer	13%	26%	61%	37,658	6%
Wooded Riparian	23%	54%	23%	39,207	6%
Wetland	6%	14%	80%	20,198	3%
Montane Meadow	43%	46%	10%	17,961	3%
Agriculture	98%	2%	0.3%	19,203	3%
All Systems by Quality	26%	27%	47%	515,343	81%*

Growing Season – Mule Deer

Considering all ecological systems across the growing season range, approximately 72% is in either the high or moderate category for habitat quality for mule deer (Table 9, Figure 20). That number was approximately 87% in the forage quality model, so there was some reduction in quality overall when the additional habitat quality metrics were incorporated. This is an absolute reduction of 15%, which translates into a roughly 17% loss of area from the high or moderate quality categories once the additional habitat quality metrics were incorporated (15 divided by 87). For the largest systems within growing season range for elk (Spruce-Fir and Aspen), the majority of each system is still in the high or moderate quality categories for habitat at 76% and 88%, respectively. Though Wetlands and Wooded Riparian cover a relatively minor proportion of the total area within the growing season range, these systems make important contributions. In particular, we consistently observed that the wetlands in the ecotone between subalpine (especially Spruce-Fir) and Alpine throughout the Watershed were very heavily used due to the abundance of palatable forage. As with the larger systems, a majority of the Wetlands and Wooded Riparian are high or moderate quality habitat (60% and 77%, respectively).

***Table 9. Proportion of each ecological system within* growing season *range for* mule deer *represented by high, moderate, and low quality* habitat.** *There may be slight discrepancies due to rounding. *The total area of the growing season range includes other land covers not included here, such as golf courses and lawns, built-up areas, bare rock, and open water, which are not habitat.*

Ecological System	Low Quality	Moderate Quality	High Quality	Total System Acres[7]	% of Modeled Winter Range
Alpine	72%	26%	2%	33,924	5%
Aspen	12%	37%	51%	101,923	16%
Oak/Mixed Shrub	54%	35%	11%	20,062	3%
Pinyon-Juniper	82%	14%	4%	1,425	<1%
Sagebrush	68%	26%	5%	14,907	2%
Spruce-Fir	24%	19%	57%	242,815	38%
Other/Mixed Conifer	12%	25%	63%	37,658	6%
Wooded Riparian	23%	56%	21%	39,215	6%
Wetland	40%	52%	8%	20,208	3%
Montane Meadow	43%	48%	9%	17,968	3%
Agriculture	97%	2%	0.3%	19,203	3%
All Systems by Quality	27%	28%	44%	515,385	81%*

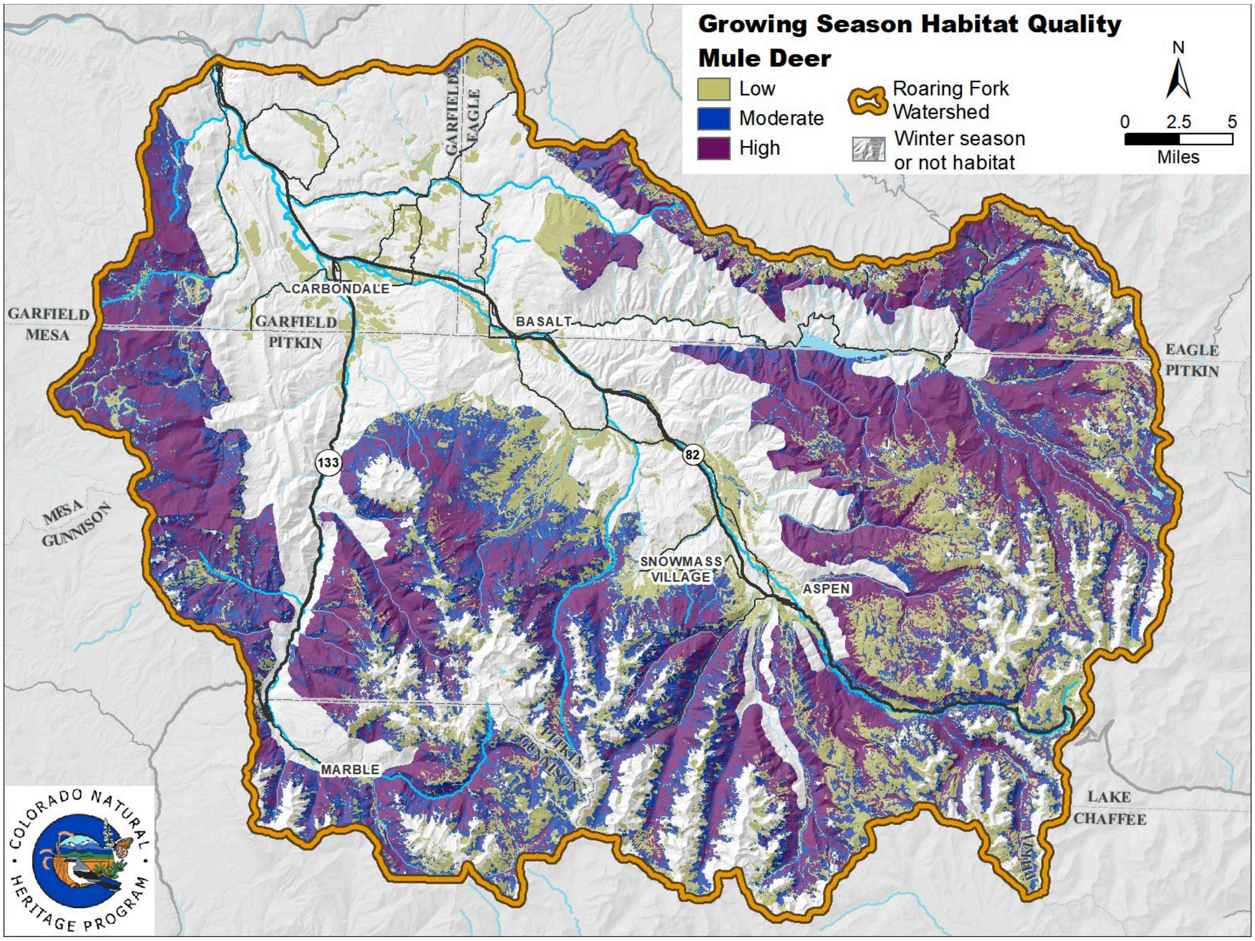

Figure 19. Relative habitat quality for mule deer during growing season.

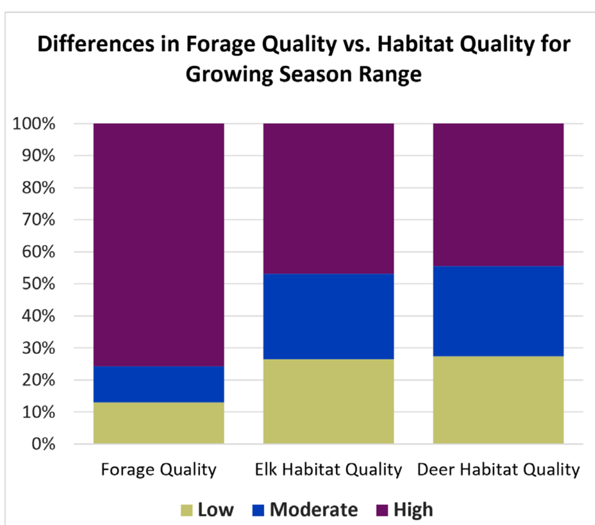

Figure 20. Comparison of forage quality and habitat quality in growing season range.

Habitat Quality by Land Ownership

Protected areas such as national forests, city and county open spaces, and state wildlife areas do not fully encompass the "critical habitats, population source areas, and migration routes for wild populations" (Defries et al. 2007, p. 1032) necessary to sustain wildlife populations and landscape-scale ecological processes. Private lands often provide important wildlife habitat (Gosnell, et al. 2007, Hurst and Kreuter 2021).

According to our habitat quality models, the proportion of public and private lands characterized as low, moderate, and high quality is spread relatively evenly for elk and mule deer winter habitat within both the modeled winter range and the known winter range, regardless of ownership type (Figures 21 and 22). Private landowners control about a third of the habitat within modeled winter range, but almost half of the habitat within the known winter range. Since habitat on private lands is more vulnerable to loss (e.g., to development), what happens on private lands could have a significant impact on the proportion of low quality habitat within the known winter range. Of particular interest are private lands associated with winter concentration areas and severe winter range, especially those areas separated by movement pinch points.

Growing season habitat is skewed more strongly toward high and moderate quality habitat on public lands, and toward low quality habitat on private lands (Figure 23). This is true for both elk and mule deer. Private lands make up a much smaller proportion (~14%) of the growing season habitat, but of these private lands, around 30% offer high or moderate quality habitat. These would be important places to consider for conservation, especially where they connect to higher quality habitats on public lands.

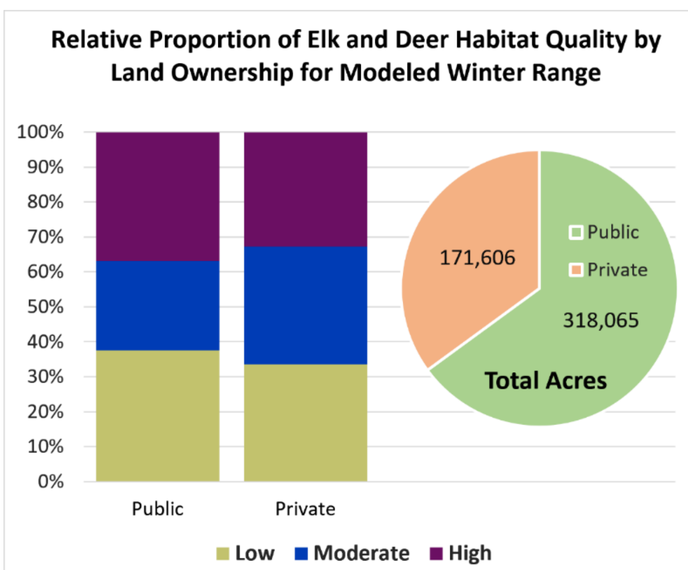

Figure 21. Relative proportion of elk and mule deer habitat quality by land ownership for modeled *winter range.*

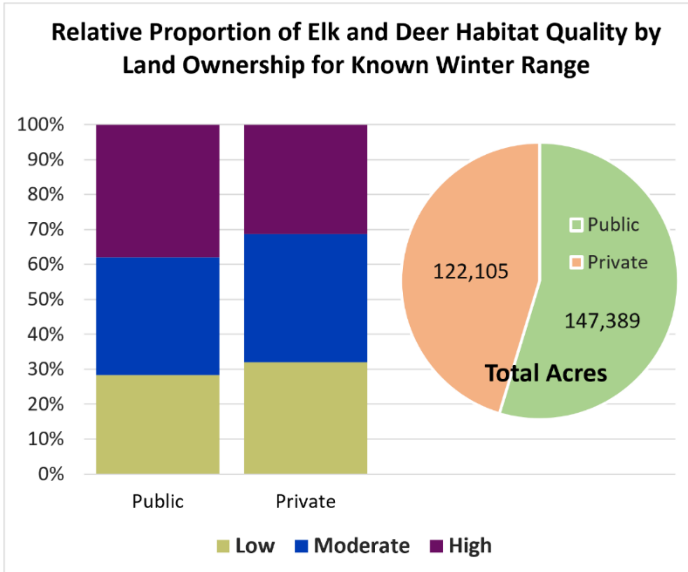

Figure 22. Relative proportion of elk and mule deer habitat quality by land ownership for known winter range.

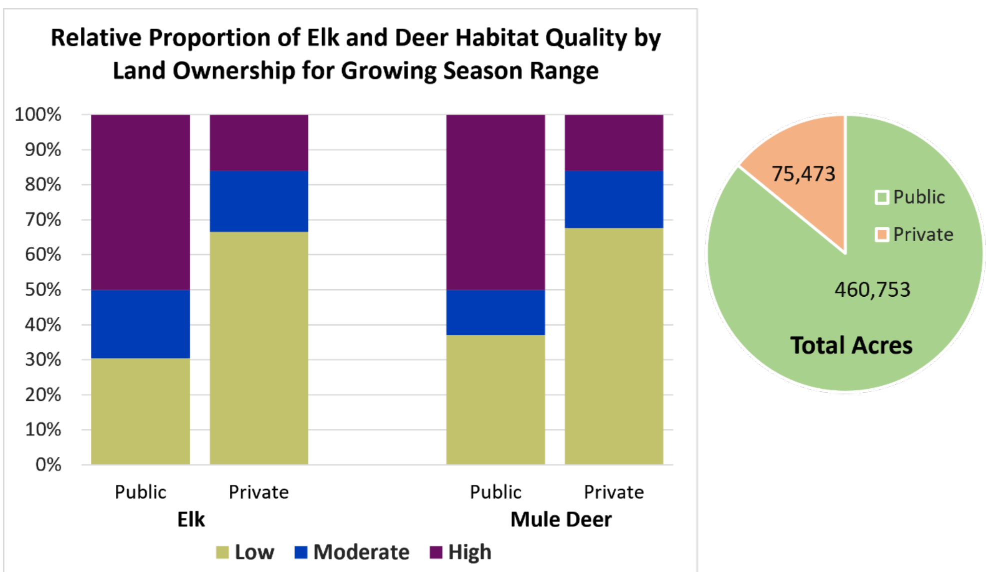

Figure 23. Relative proportion of elk and mule deer habitat quality by land ownership for growing season range.

Likely Movement Corridors

Lastly, likely movement corridors were generated to augment the habitat quality model (see Appendix I for detailed methods). These potential corridors reflect opportunities for movement within the transitional zones between winter and growing season ranges for elk and mule deer (Figure 24). Figure 24 shows large areas of high and moderate quality habitat well-distributed across the Watershed, with multiple options for animal movement up and downslope, through and between habitat patches within winter and growing season ranges. What is clearly missing is safe passage between habitats on opposite sides of the major transportation corridors, particularly Highways 82 and 133. That animals try to move between habitats on opposite sides of these corridors is borne out by the significant number of road kill incidents (see Appendix L, Figure L-1). For example, Cattle Creek has large areas of high quality habitat on both sides of the creek, and there are also large areas of high quality habitat across Highway 82, west of the confluence of Cattle Creek and the Roaring Fork River. One of the highest densities of movement pinch points in the Watershed occurs along this section of Highway 82. Similar situations occur along much of Highway 82, especially the stretch approaching Aspen from the north, around Snowmass Village, and along Highway 133 near Carbondale. These areas, and any others where higher quality habitats are bisected by well-traveled roads, would be potential opportunities to improve landscape connectivity and safe passage for wildlife. Places where pinch points occur between high quality habitat and a mix of landownership types offer excellent opportunity for public/private partnerships to improve connectivity. For example, around Missouri Heights, even small patches of high quality habitat are used by elk and mule deer. Improving connectivity in places such as these would increase the value of these habitats.

When interpreting the likely movement corridors map, be aware that these areas should *not* be considered migration corridors (see CPW SAM migration corridors). These modeled movement corridors represent the most permeable paths of least resistance based on land cover and land use. The social learning and socioecology of the animals can sometimes dictate or override these routes. There is uncertainty inherent in the probability of use within these corridors. This information can be refined once actual movement data from CPW's ongoing collar study become available.

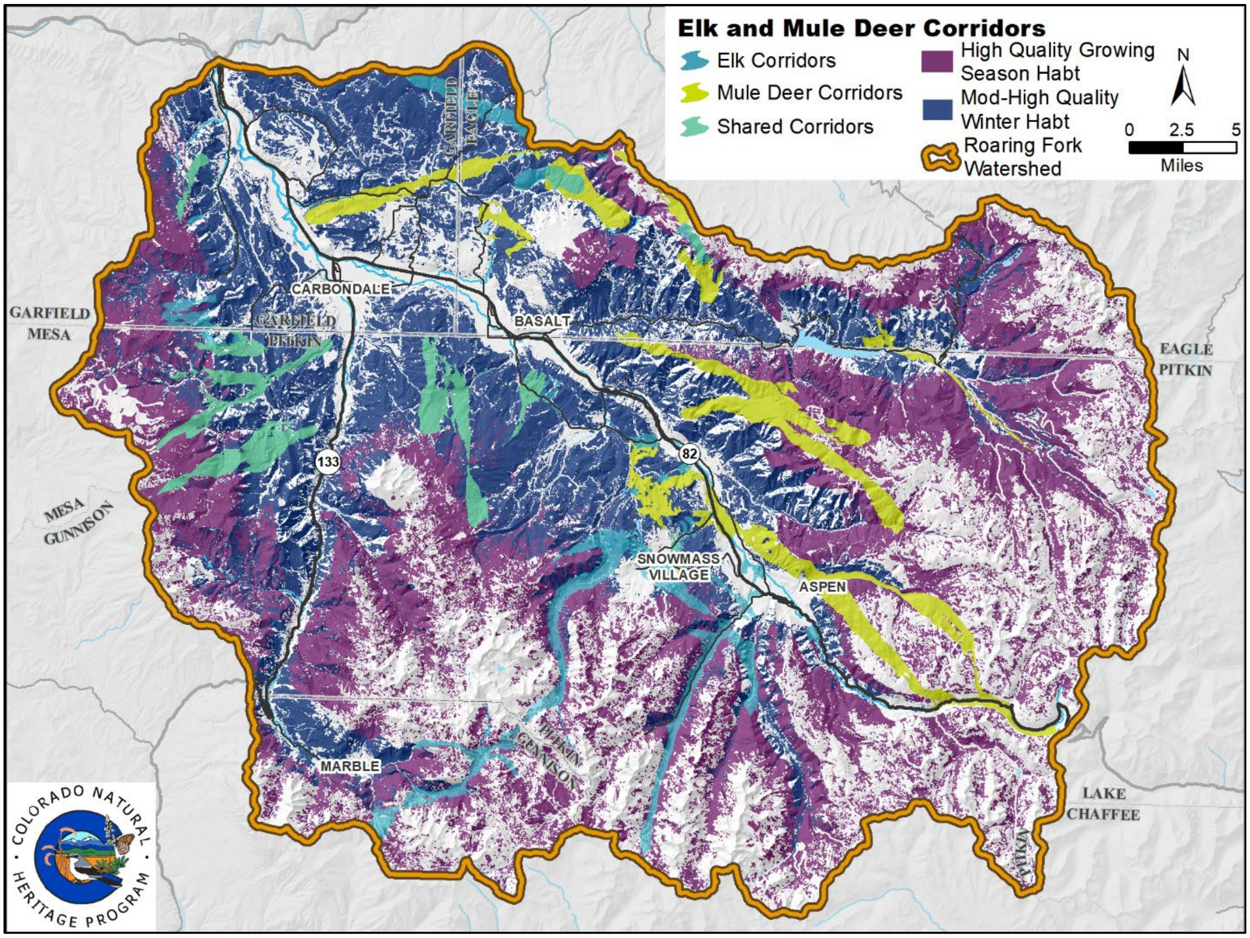

Figure 24. Modeled likely movement corridors for elk and mule deer within the Roaring Fork Watershed.

Habitat Quality – Rocky Mountain Bighorn Sheep

Bighorn sheep, once a common species in the watershed, currently have fewer than 200 individuals (pers comm., J. Mao, CPW). The Crystal River drainage, Maroon Bells area, and north of the Fryingpan River are the primary portions of the Watershed where one can still find bighorn sheep.

The habitat quality models for bighorn sheep in the Roaring Fork Watershed depict large areas that are not currently occupied but have the potential to support bighorn sheep herds. Winter habitat (approximately 182,000 acres, Figure 25) is more limited than growing season habitat (386,000 acres, Figure 26), but the winter and growing season ranges are adjacent to each other.

Most (85%) of the winter and growing season habitat is on public land (Figures 27 and 28). For both winter and growing season, public lands have a larger proportion of the habitat classified as moderate to high quality. Private lands classified as moderate to high quality are often adjacent to public lands and are critical to bighorn sheep populations.

Figure 29 shows the winter and growing season habitat models in relation to the current overall bighorn range, as defined by CPW's SAM for bighorn. There are several areas with moderate and high quality habitat that currently do not have bighorn sheep. These areas, and others, may offer an opportunity to expand the bighorn sheep population. It is important to note that the last active public land domestic sheep grazing allotment was retired in 2019. Thus, one of the greatest obstacles to bighorn sheep recovery, disease transmission via domestic livestock, was removed from public lands. There is still a need to isolate bighorn sheep herds from one another to reduce disease transmission; these models highlight areas where the option of re-introducing bighorn sheep into isolated areas may be viable. This study recognizes that it is generally advantageous for elk and mule deer to have seasonal migrations between high and low elevations and for individuals to mix among the various fluid herds to maintain healthy genetics. In the case of bighorn sheep, however, the lingering presence of disease acquired from domestic sheep, goats, and perhaps cattle, means that keeping bands and herds of bighorn sheep isolated one from another is advantageous. Understanding this, the mapping identifies occupied and potential habitat in a way that allows protection and restoration efforts to be planned to avoid disease transmission caused by mixing of individuals among bands and herds of bighorn sheep.

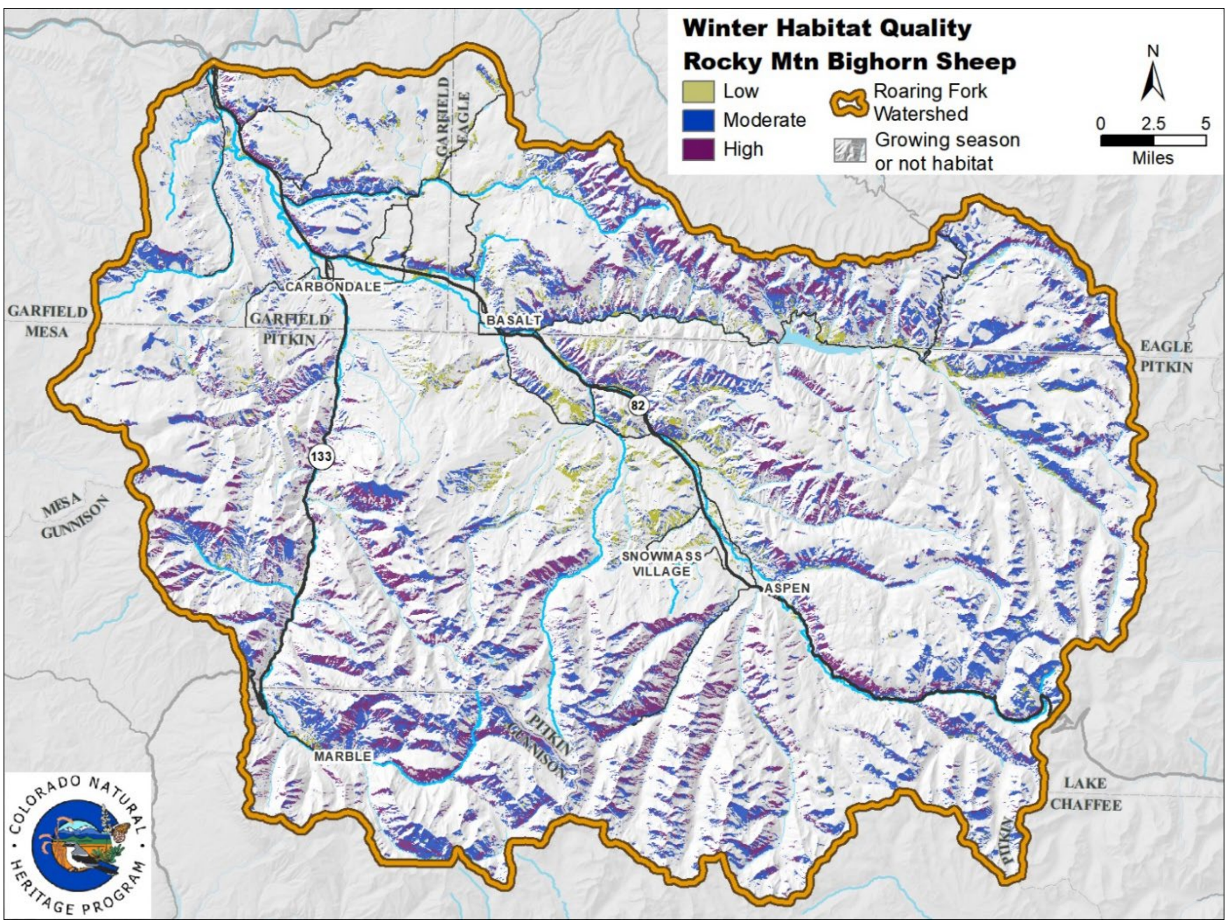

Figure 25. Relative habitat quality for Rocky Mountain bighorn sheep during winter.

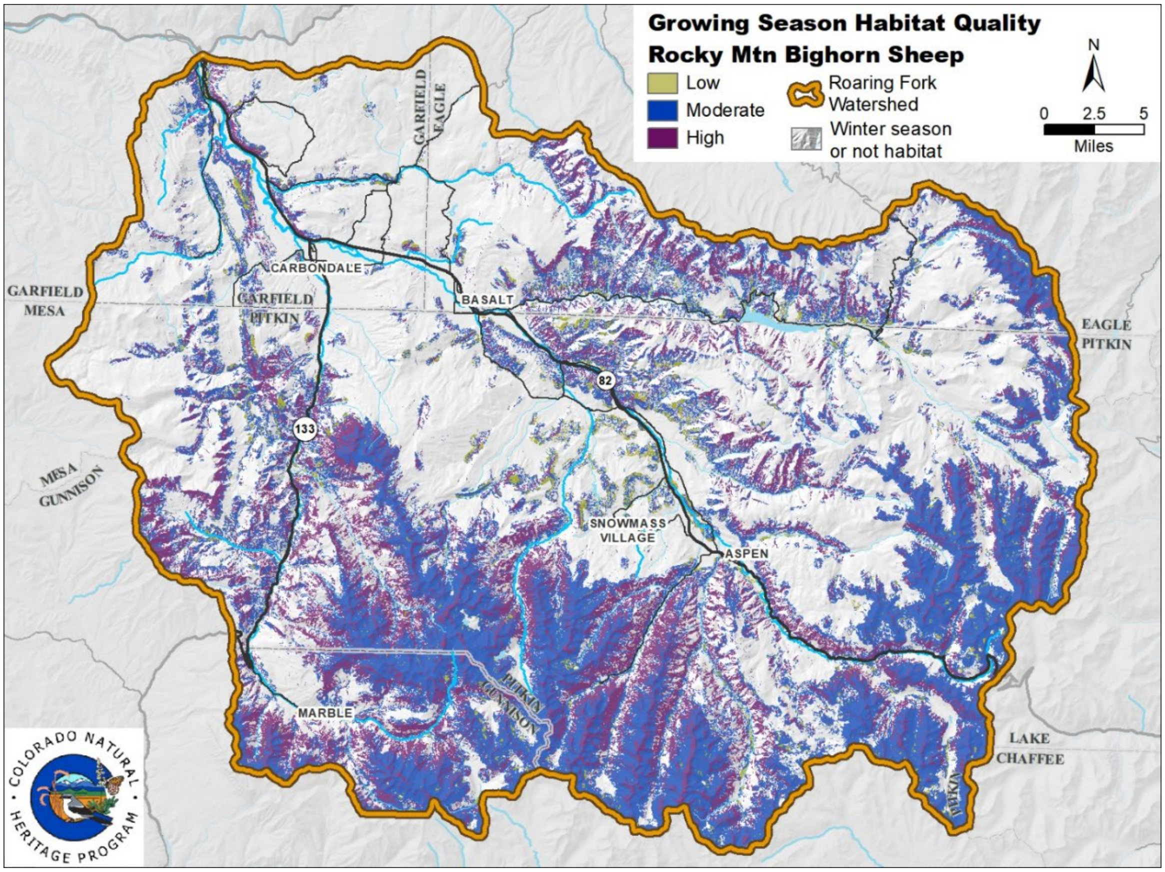

Figure 26. Relative habitat quality for Rocky Mountain bighorn sheep during growing season.

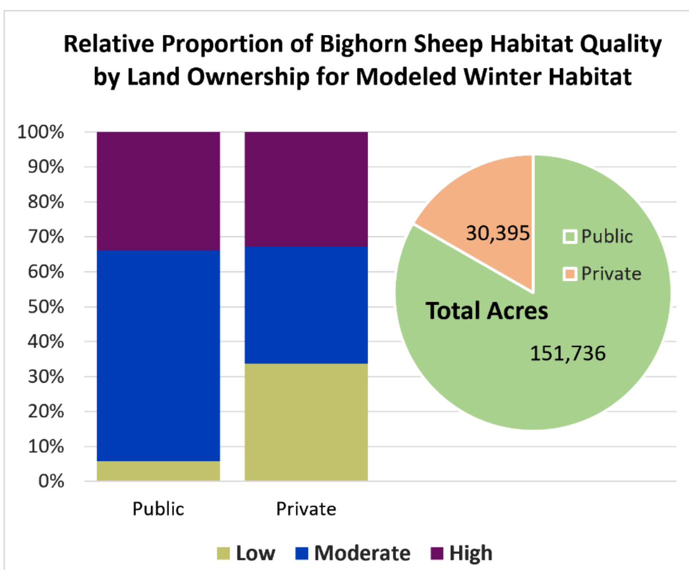

Figure 27. Relative proportion of bighorn sheep habitat quality by land ownership for modeled winter habitat. *The acreages reflect CPW's winter habitat suitability model and summer + lambing suitability models without limiting them to CPW SAM known ranges.*

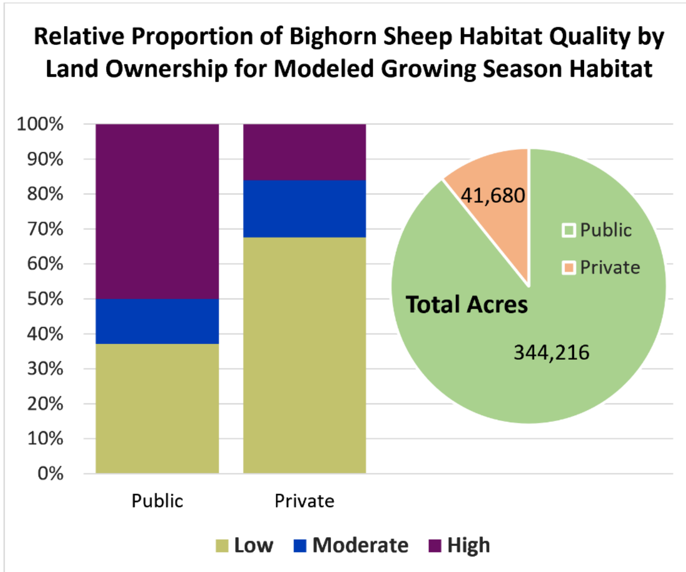

Figure 28. Relative proportion of bighorn sheep habitat quality by land ownership for modeled growing season habitat. *The acreages reflect CPW's winter habitat suitability model and summer + lambing suitability models without limiting them to CPW SAM known ranges.*

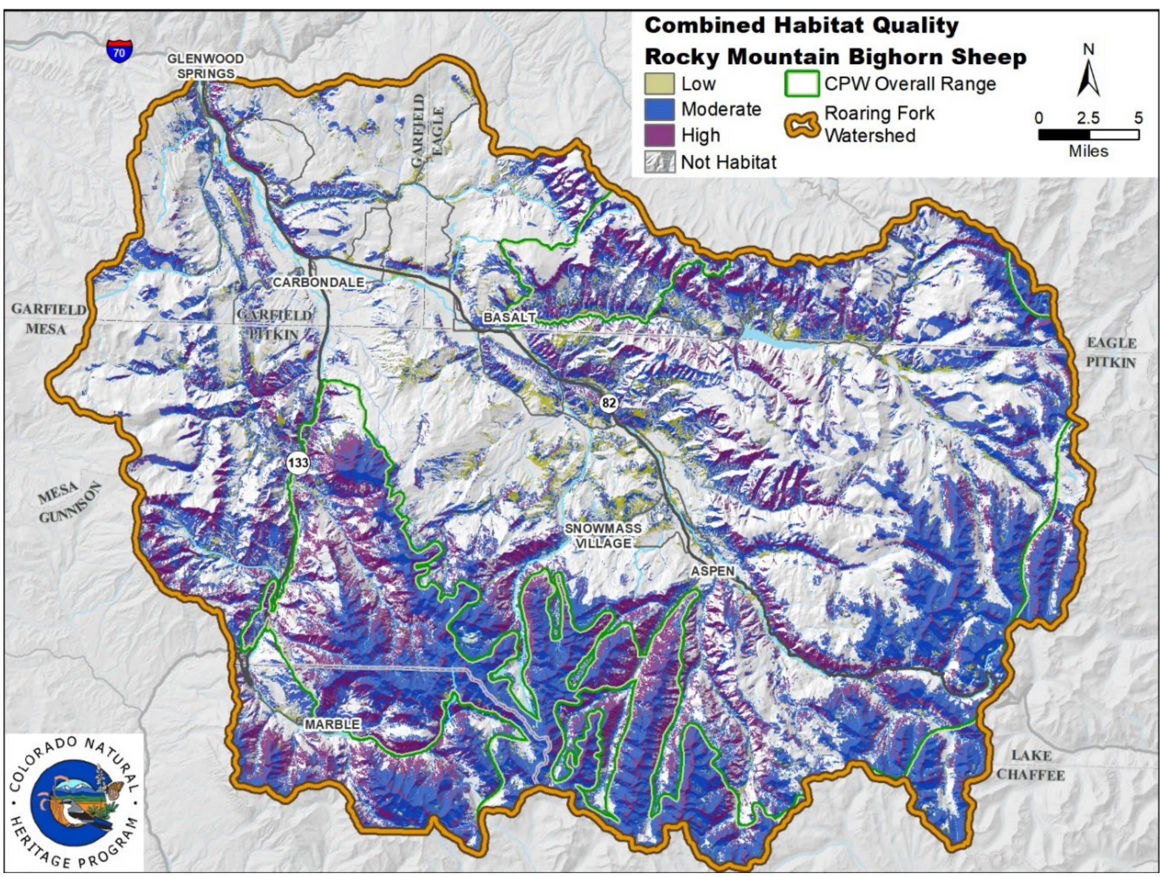

Figure 29. Relative habitat quality for Rocky Mountain bighorn sheep with winter and growing seasons combined, plus the extent of CPW SAM overall range for bighorn in the Watershed.

Conservation Importance

Defining ecological attributes of interest and concern, including flagship species, biodiversity elements of concern, representative habitats, etc., and then delineating the spatial extent of those features is a key step toward conserving the ecological functioning of protected areas and the surrounding landscape (Defries et al. 2007). The Conservation Importance (Figure 30) component of this study, as introduced in the Methods section, combined Key Areas and Biodiversity Importance data to create an overall indication of where general conservation needs are highest in the Watershed.

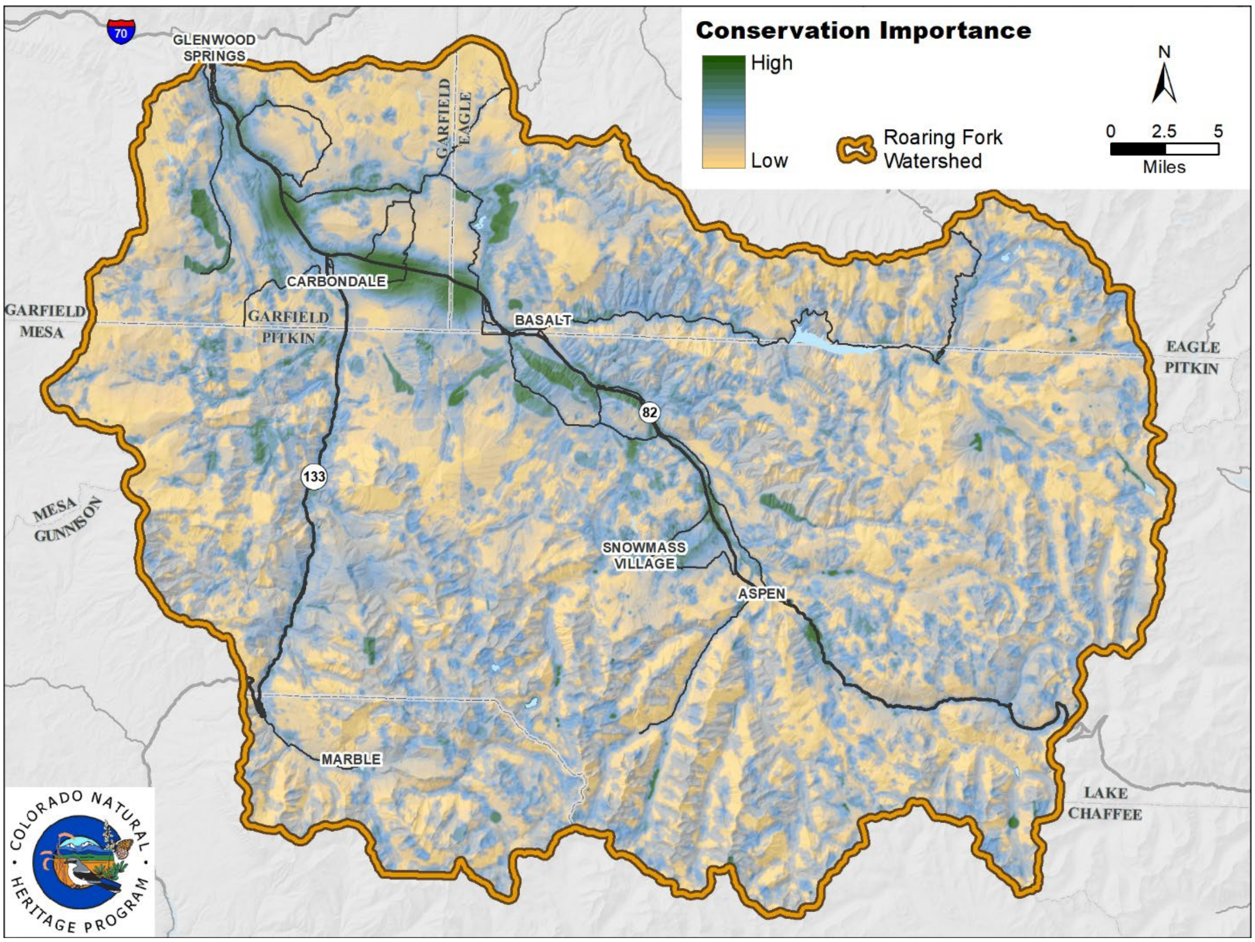

Figure 30. Overall conservation importance based on available data. *Please note that absence of evidence is not evidence of absence, and all management decisions should be confirmed with on-the-ground reconnaissance.*

These hotspots also highlight important "zones of interaction" (Defries et al. 2007) where concentrated human development, land use, and human need for ecosystem services has the potential to interfere or conflict with critical elements of biodiversity and the ecological functioning of the broader landscape. Conversely, local people are essential components for long-term conservation (Schwartzman et al. 2000).

The proximity of these conservation importance hotspots to concentrations of human populations within the Watershed (e.g., the towns of Carbondale and Basalt) suggest greater opportunity for public engagement and involvement in conservation planning and management in these locations.

Watershed Conservation and Restoration Priorities

The Watershed Conservation and Restoration Priorities map (Priority Areas Map, Figure 31) is the culmination of a multi-criteria decision process used to combine the habitat quality models and the conservation importance layers. ***The Priority Areas map demonstrates that the majority of the Roaring Fork Watershed provides large blocks of intact, connected landscapes of moderate to high conservation value based on the presence of moderate to high quality habitat for elk, mule deer, and/or bighorn, as well as multiple other elements of conservation importance.*** The Roaring Fork and Crystal River valleys, which also serve as corridors for the main transportation arteries within the Watershed (Highways 82 and 133), contain core areas of conservation importance (shown in Figure 24) where there is significant opportunity for direct conservation and/or restoration action due to the expanding influence of land use change and development.

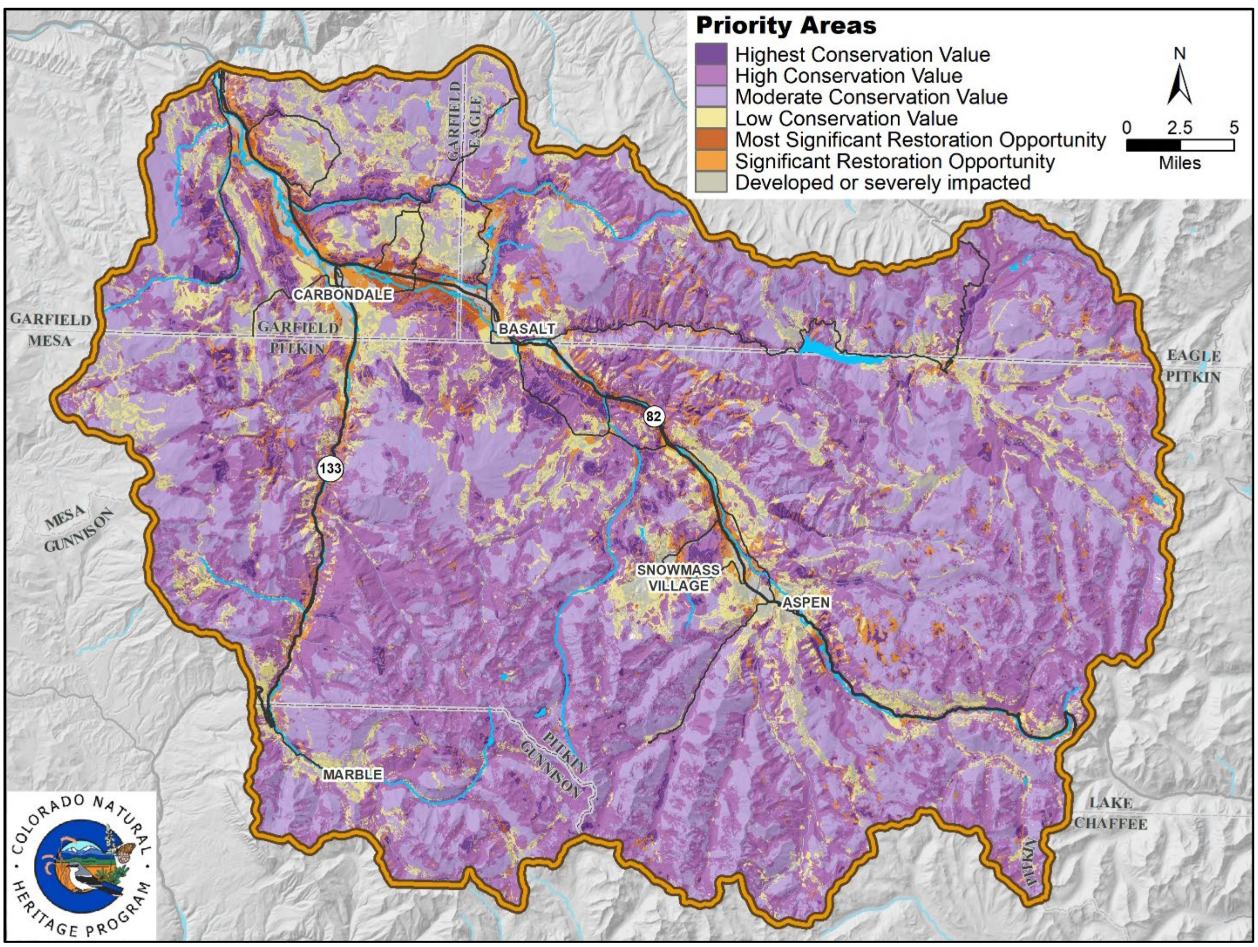

Figure 31. Conservation and restoration priorities for the Roaring Fork Watershed.

The purple areas of the map (Moderate to Highest Conservation Value categories) are those places where multiple aspects of conservation value converge. These places support:

- high to moderate habitat quality for focal ungulates (elk, mule deer, and/or bighorn)

and

- at least one other component of biodiversity importance
  - rare species
  - wetlands
  - National Audubon Society's Important Bird Areas
  - areas predicted to be more resilient to climate change by The Nature Conservancy
  - calving/lambing or wintering sites for elk, mule deer, and/or bighorn

The darker the purple, the greater the conservation value. Factors that may influence the shade of purple include whether habitat quality for focal ungulates is high or moderate, how imperiled a rare species or wetland is, and how many different components of biodiversity importance co-occur in the same place. All of the areas colored darkest purple on the map support high quality ungulate habitat and have documented occurrences of highly ranked biodiversity values (e.g., multiple different values co-occurring, very rare species or wetlands). The areas colored lightest purple are those places where either habitat quality for ungulates is moderate and there is at least one documented occurrence of another biodiversity value, or habitat quality for ungulates is high but there are no documented occurrences of other biodiversity values.

Areas colored gold on the map (Low Conservation Value category) have been deemed of lower conservation value *at this point in time*. These are places that:

- offer moderate habitat quality *for focal ungulates* but no *known* occurrences of any of the other biodiversity values that we considered in this study

or

- have low habitat quality for focal ungulates but support two or three other biodiversity values.

Interpretation of the gold places on the map hinges on understanding several key concepts. First, this map represents what we know right now. The fact that we do not currently have documentation of other biodiversity values does not necessarily mean that they don't exist. Gold color on the map could represent data gaps with respect to rare species, wetlands, or any other of the biodiversity values we considered in this study. These may be places where additional field inventory is needed. Because these areas offer moderate (at best) or low quality habitat for the focal ungulates, they may (or may not) represent habitat improvement opportunities. Other potential reasons for low conservation value could include a high level of human disturbance, a natural landscape that has low forage production (e.g., dense lodgepole stand with little understory, steep slopes). It is also possible that, due to the importance we placed on forage quality in this study, some gold areas could be places that were drier during our field visits, and therefore lacking in forb abundance and diversity (forbs are closely tied to moisture, and can be highly variable from year to year). Finally, some habitats are naturally less significant for focal ungulates but still offer crucial resources for other species. Pinyon-juniper is an example of this situation, where many bird species require pinyon pine or juniper species for food and successful breeding.

Red and orange areas on the map are places that:

- have low habitat quality for focal ungulates (often due to high human disturbance)

and yet

- still support highly ranked biodiversity values

Many of these areas are found along major transportation corridors, which are often adjacent to rivers and streams. The presence of more concentrated human infrastructure in and near these places lowers the habitat quality for focal ungulates, and impedes animal movement between higher quality habitats. The darker red color indicates the presence of multiple occurrences of biodiversity values and more imperiled species and wetlands. All of these red and orange areas are places where restoration of habitat, ecosystem function, and/or landscape connectivity could make significant contributions to the overall status of biodiversity across the Watershed.

The gray areas on the map are those that are dominated by human infrastructure, and thus offer little functional natural habitat for the focal ungulates or other biodiversity values. Human-dominated landscapes do, in fact, offer habitat for some species who can live in these settings. However, for the purposes of this study, we considered these areas as not habitat. Note that barren lands, exposed rock, and naturally disturbed areas such as eroded soils are also sometimes included in this category, depending on how they were mapped in the underlying land cover data.

For all map categories, there are a variety of reasons why a particular area could fall within that category. Though the labels we chose for these categories suggest a strategy approach—conservation or restoration—these should be interpreted as broadly defined concepts rather than specific modes of action. When using the Priority Areas map to evaluate potential conservation or restoration sites or to design projects, it is important to review the multiple data layers that went into developing the priorities map. In addition, it is crucial to assess any site in the field before making any management changes.

Helpful Hints for Using the Priority Areas Map

After the completion of the analyses and concurrent with this writing, we conducted approximately 15 “test drives” of the Priority Areas map with individual Science Team members and other interested parties across the Watershed, with dual goals of vetting the map and assisting viewers in the proper interpretation of the map. Most of these test drives focused on places where elk and mule deer were a key interest of the reviewers and followed a similar pattern:

1) Review the forage quality models for elk and mule deer (if the project area is in a seasonal transition zone, review both winter and growing season forage quality).
2) Review CPW’s winter range maps, especially winter concentration areas and severe winter range.

3) Review the landscape disturbance model.

4) Review the habitat quality models for elk and mule deer.

5) Review pinch points and movement corridors layers.

5) Then review the Priority Areas map.

By following this approach, one can begin to build a story for a project area. For example, in the area around Snowmass Village, there are patches of severe winter range and winter concentration areas for elk. The overall forage quality is a mosaic of high to low quality, and some places have a high density of human disturbance, which in turn reduces habitat quality. By reviewing the overall conservation and restoration priorities in the Priority Areas map, we can conclude that some agricultural lands that are considered moderate quality for forage but low quality for habitat would benefit from conservation activities that reduce fragmentation. Conserving agricultural lands in this area would provide valuable connectivity to known winter concentration and severe winter areas, thus providing elk and mule deer with improved winter habitat, as well as the other ecosystem services agricultural lands provide (e.g., support for wildlife access to riparian zones and public lands on valley sides, security during vulnerable times).

Figures 32 through 35 show a second example of a step-by-step approach to using and interpreting the series of complex data and models that culminate with the Priority Areas map for a different area of the Watershed near Carbondale. Site photo icons in Figure 32 represent three on-the-ground field assessment locations. All three locations occur within elk and mule deer winter range, severe winter range, and winter concentration areas according to CPW SAMs. These sites span low, moderate, and high quality winter forage (Figure 33). Figure 34 displays the habitat quality model where elements of shelter and anthropogenic disturbance modify forage quality values. Note the impact of Highway 133, running within the Crystal River floodplain, on the habitat quality, diminishing moderate quality in the forage model to low quality in the habitat model. Figure 35 illustrates the areas around Highway 133 and N Thomas Road, south of Carbondale, where restoration or targeted conservation efforts may be needed to connect larger cores of habitat and significant elements of conservation importance.

Figure 32. Site photo icons represent locations of three field assessments. *These locations all occur within elk and mule deer winter range, severe winter range, and winter concentration areas. This area is southwest of Carbondale on the west side of the Crystal River and Highway 133 and includes both public and private lands.*

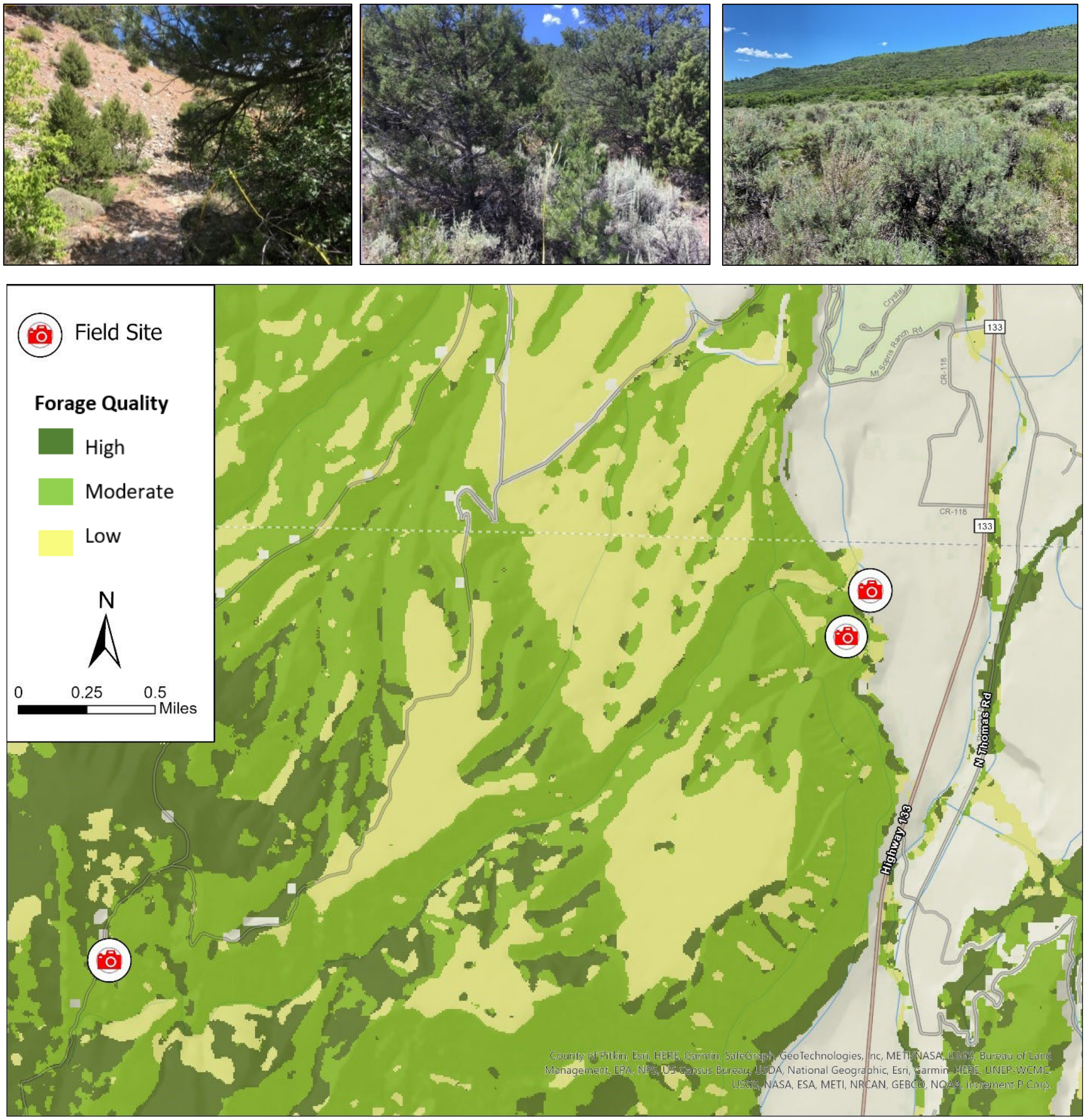

Figure 33. Site photos demonstrate the range of forage qualities documented across three field assessment locations for winter range southwest of Carbondale on the west side of the Crystal River and Highway 133. *Field data from these sites were used to develop the forage quality model depicted here.*

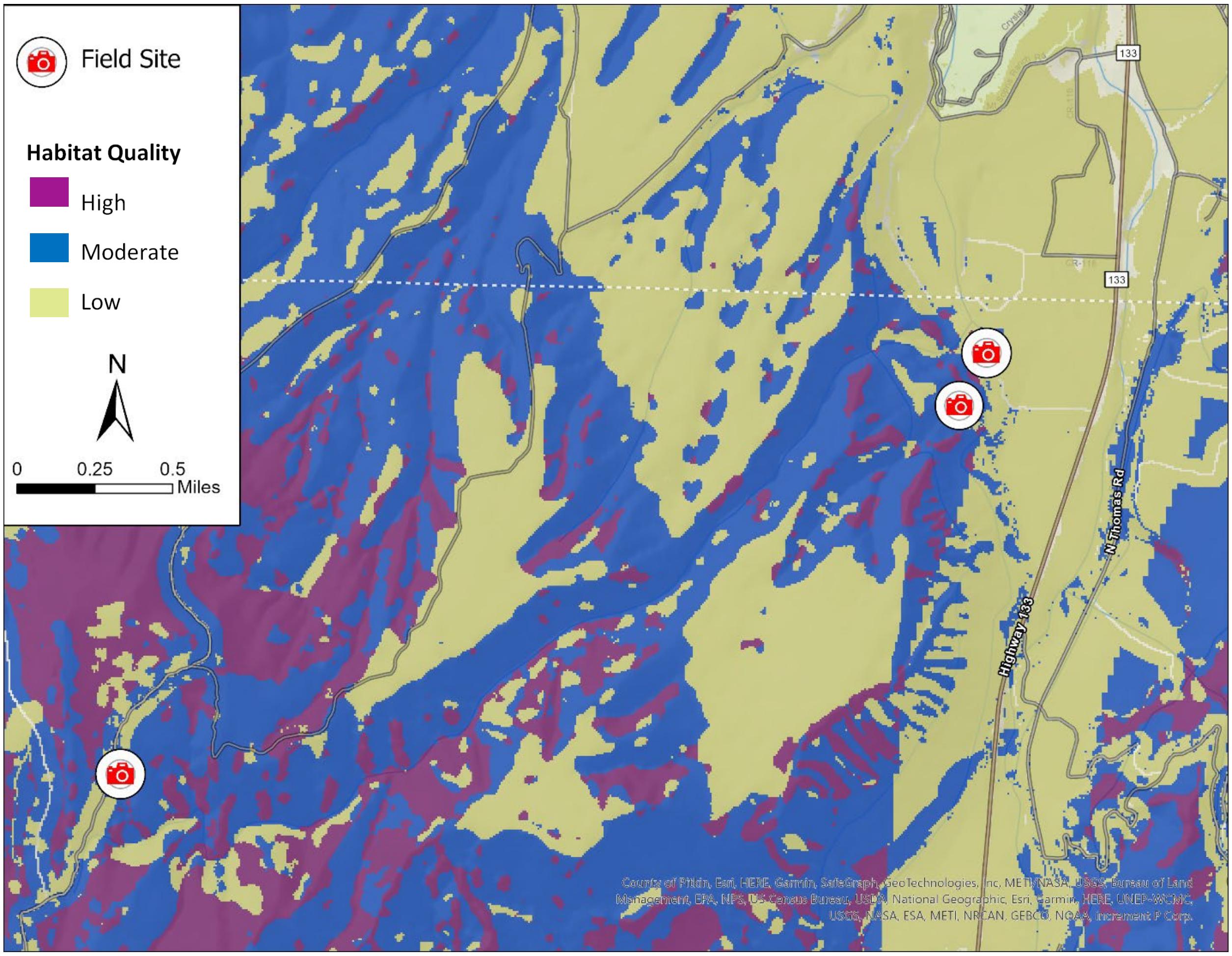

Figure 34. The forage quality model combined with elements of water, shelter and anthropogenic disturbance (see Methods section) to create the habitat quality model seen here. *Note increase in "Low" quality habitat along Highway 133 relative to previous forage quality model. This change is reflects the impact of Highway 133.*

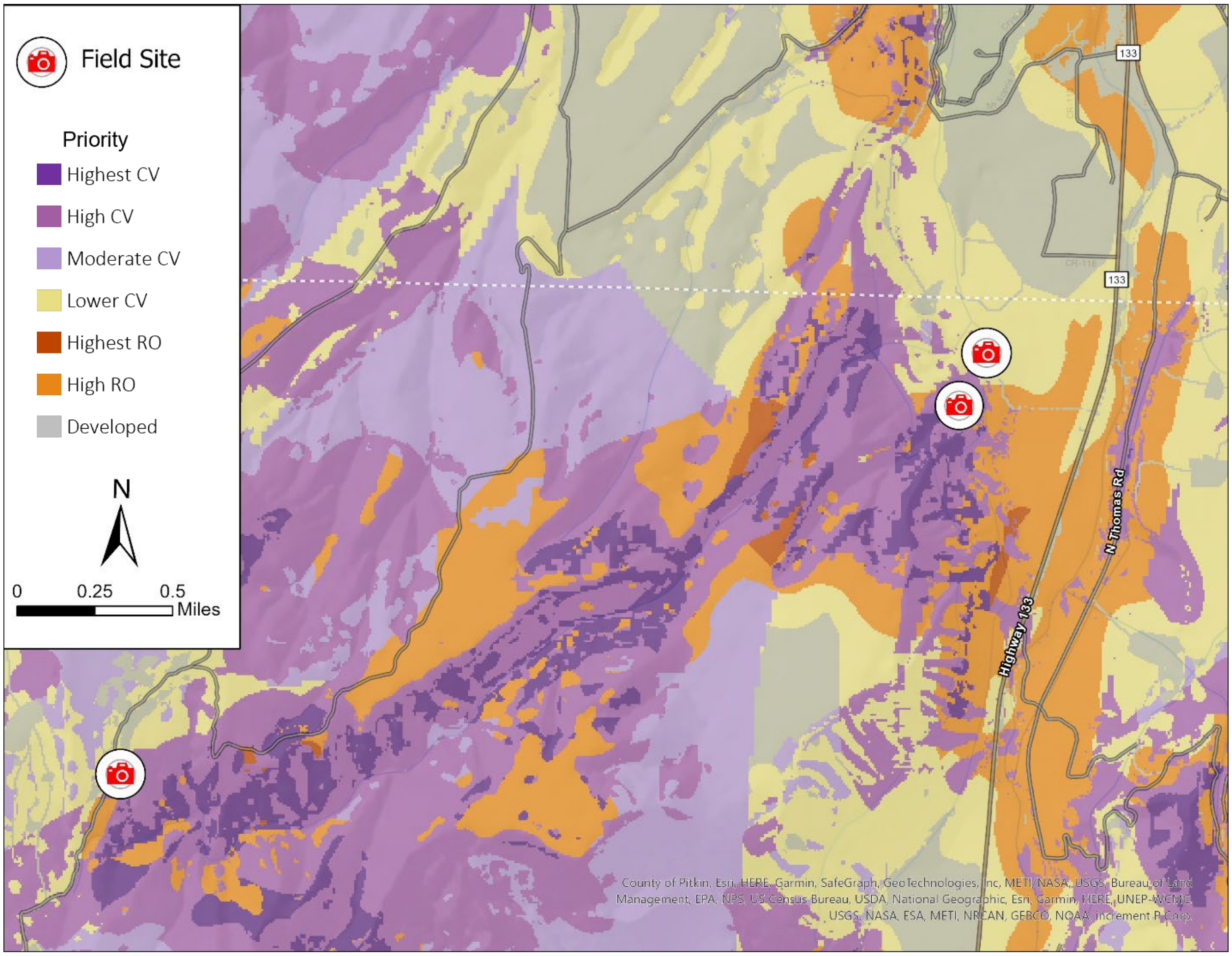

Figure 35. The priority areas model reveals the likely need for restoration activities in and around Highway 133 and N Thomas Road, south of Carbondale to connect the larger cores of habitat in this area that support elk and mule deer during winter, as well as the other biodiversity values reflected in the conservation importance model. *CV = Conservation Value; RO = Restoration Opportunity.*

CONCLUSIONS AND RECOMMENDATIONS

The nearly 1-million-acre Roaring Fork Watershed on the West Slope of the Colorado Rocky Mountains is experiencing a growing population of citizens that live, work, and recreate in the region. “Given that people and wildlife often select similar biophysical features of the landscape, land-use change frequently occurs in areas of high biological productivity, potentially having disproportionate effects on wildlife (Hansen et al. 2005, Leu et al. 2008)” (Johnson et al. 2017, p. 578). Consequently, the region’s biodiversity and natural landscapes are being disturbed, fragmented, and squeezed by these growing human-induced stressors. In addition to the stressors from the ever-growing human footprint, climate change is impacting the watershed. Colorado is currently experiencing a 22-year megadrought and it is predicted to potentially last an additional 8 years (Williams et al. 2022). The megadrought is notable for its severe impacts on forest ecosystems, wildfire and reduced soil moisture, all of which greatly affect habitat quality.

This study relied on field-based vegetation data combined with spatial analysis using remotely sensed data to develop a series of iterative models that advance our watershed-wide understanding of forage quality and habitat quality for focal ungulates, and areas of critical importance for biodiversity and ecological resilience. The majority of this study’s on-the-ground data collection was dedicated to assessing the nutritional quality and quantity of vegetation available to elk and mule deer across the Watershed’s broad elevational gradient. The nutritional landscape drives population dynamics of these wide-ranging focal species (Hurley et al. 2017, Cook et al. 2016, Tollefson et al. 2011, Tollefson et al. 2010, White et al. 2010, Cook et al. 2004). Understanding ungulate forage (both nutritional content and productivity) is becoming increasingly important given climate-related changes in habitat and declines in western U.S. ungulate populations (McCarley et al. 2020 citing Montieth et al. 2015, Schrempp et al. 2019, White et al. 2010). Prior to this study, the vegetation maps available for the Watershed were too coarse to sufficiently characterize ungulate forage quality spatially and temporally. To understand the nutritional landscape, our novel approach started first with fine-scale vegetation transect data collected across 231 sites to document forage availability and quantity (i.e., relative percent cover of forbs, graminoids, trees and shrubs and palatability (i.e., nutritional quality; see Appendix D).

Our forage quality models suggest that forage is not a limiting factor in either winter or growing season ranges for elk and mule deer. Seventy percent of the modeled winter range and 80% of the known winter range was classified as high or moderate forage quality, and 87% of the growing season has high to moderate forage quality. Winter range offers an abundance of shrublands with palatable, nutritious shrubs. In the growing season range, an abundance of rich aspen forests, subalpine meadows, and open spruce-fir forest intermixed with wet meadows and willow carrs offer highly nutritious and abundant forage for elk and mule deer throughout the Watershed. The abundant good forage quality in mesic and wet meadows in the growing season range allows ungulates to spend less time grazing and more time resting, and therefore to gain the body weight necessary to survive winters. Wet and moist sites offer abundant forage produced by a variety of plants un-matched by the adjacent dry forest; moist and wet meadows can offer between 1,330-2690 pounds/acre compared to 170 pounds/acre in the adjacent dry forests (Patton and Judd 1970). Thus, wet areas within the growing season range are critically important.

It is important to note however, that the value of these core areas is reduced when availability of other habitat resources (water, shelter) and anthropogenic disturbance are considered in the habitat quality models. This is true for both winter and growing season ranges. Land-use changes (e.g., residential development) result in direct destruction and fragmentation via infrastructure construction, and indirect habitat degradation or loss via animal avoidance of infrastructure (Northrup et al. 2015, Sawyer et al. 2009, Vogel 1989,) and decline in floristic quality (Decker et al. 2017). Large core areas occur on both private and public lands, but are often fragmented by highways or modified landscapes. Anthropogenic pinch points (e.g., areas with high road kill) reveal the animals' desire to move between areas of relatively higher quality winter habitats. Thus, it is important to ensure good connectivity between areas of high and moderate quality habitat. We found that even small areas within developed sites (e.g., Missouri Heights) are used by elk and mule deer as they move from one high quality habitat area to another. Strategies to improve connectivity among these areas include safe passages along Highways 82 and 133 in carefully chosen areas. For areas like Missouri Heights, understanding current movement and developing a safe corridor with low human disturbance (e.g., without human structures) could assist wildlife in safe movements between areas of high quality habitat.

Recommendations

The recommendations offered here are a suite of strategies that could be undertaken to safeguard higher quality habitats, improve lower quality habitats, and maintain or improve connectivity across the Watershed. The list that follows is not presented in priority order. Priority will be different for each stakeholder, depending on their mission, goals, and interests.

This study did not address ideal population numbers for focal species in the Watershed or the possible reasons behind herd decline(s). Those questions fall within the purview of CPW, and that agency is actively engaged in those inquiries. While we can reasonably assume that some factors related to habitat (degradation, development) contribute to the status of the herds alongside other causes, this study does not address causality. Nonetheless, we believe implementation of the strategies outlined in this report—protecting high quality habitat and connectivity where possible, and improving habitat quality and connectivity where needed—will contribute toward the future viability of the elk, mule deer, and bighorn herds, as well as all the other components of the Watershed's biodiversity.

The Big Picture

The results of our study and the feedback we received during our test drives with the Science Team, private owners of large holdings, local caucuses, and more, led WBI and CNHP to four "big ideas" for moving forward with conserving biodiversity in the Roaring Fork Watershed.

Big idea # 1 – "Stitching it back together." Reconnect large landscapes that have been fragmented in the Watershed. This will improve habitat quality for deer and elk, and therefore hopefully restore and maintain healthy populations of these species. Using the forage and habitat quality models, CPW's SAM maps, and our connectivity model can help identify places where improved connectivity is needed. Examples of key opportunities include areas around Cattle Creek, Missouri Heights, and Carbondale (see Figure 24), but there are others. Opportunities for public/private partnerships exist in many places.

Big Idea # 2 – Guide development and land conservation decisions to avoid additional fragmentation and maintain connectivity amongst swaths of large intact landscapes. Any introduction of additional infrastructure or disturbance (including roads and trails) will affect habitat quality. Careful consideration of potential impacts are especially needed for areas associated with ungulate winter concentration areas and severe winter range, areas that serve as movement corridors through or between high or moderate quality habitats, areas where restoration could raise habitat quality scores and/or improve connectivity, and wetlands and wet meadows in the ecotone between subalpine forests and the alpine. Public/private partnerships will be key to success in many of these places.

Big Idea # 3 – Protect large, isolated landscapes for bighorn sheep. Because disease transmission is an issue for this species, these populations need to be isolated. Recovering the State's and region's bighorn sheep population is a widely shared goal among conservationists and wildlife managers. This goal serves as a clear rallying point to generate support for protecting and restoring the natural biodiversity that is critical to healthy ecosystem functioning. And "Save the bighorn sheep" is a much more tangible goal than the amorphous idea of saving biodiversity. Yet saving the bighorn sheep habitat (and elk and deer habitat) undoubtedly supports all most native biodiversity in the watershed.

Big Idea # 4 – "Rewet the sponge." Restore and protect wetlands throughout the Watershed. Wetlands, especially in growing season and transitional areas offer abundant high quality forage. Nearly one-third of the Watershed is blanketed with upper to high elevation conifer forests where 80% of annual precipitation is captured as snow and preserved in cool, shady conditions. Wetlands within the ecotone between Spruce-Fir and Alpine systems were consistently observed by our field team to be very heavily used by ungulates. Minimizing human disturbance (e.g., via trails, roads) is particularly important in these areas. Elk and mule deer herds have calves during the time of year that they use these high elevation habitats, and they are especially sensitive to disturbance at this time. Restoring degraded wetlands can slow the water down, increase infiltration into the soil, assimilate nutrients, and improve forage and habitat for elk, mule deer, and an abundance of other wildlife species.

Additional Recommendations

1. Plan for the future, but act in the present. The maps and data contained herein represent current conditions. We expect these to change, albeit in unknown ways, in the coming years as the climate continues to change. Anticipating these changes will be an important component of planning for conservation and restoration strategies. For example, our models suggest that Aspen areas within the

modeled winter range will become more important habitat in future winters. Meanwhile, though, continuing to strive for improved quality where habitats occur now, as in the known winter range, is needed. High and moderate quality habitats associated with known severe winter and winter concentration areas are high priorities for conservation, as well as restoration of connectivity where needed.

2. Use these data in combination with other resources when evaluating potential conservation or restoration projects. There are at least two studies currently underway that will provide additional insights to the quality of habitats and connectivity within the Watershed when results become available. These include a collar study of elk movement by CPW, and a wetland study by CNHP. Results from CPW's collar study are still at least two years out. Final data from CNHP's wetland study are expected this year.

3. Develop tools to support efficient monitoring of habitat quality over time. The detailed field data collection used to build the forage quality model is not necessary to repeat for periodic monitoring assessments. The condensed field methods used to validate the model (described in Appendix C) would be a relatively efficient means of quickly evaluating a site for basic forage quality. The most difficult component to assess is palatability. Creating a handbook or "cheat sheet" of the most palatable species would support monitoring even by trained volunteers.

4. Revisit study assumptions and analyses when CPW's movement data become available.

5. Consult with CNHP for proper use and interpretation of the maps and data provided with this study as a regular practice to ensure the study is used to its fullest capacity. Spatial data are freely available from CNHP, and WBI will be supporting our biologists to provide as-needed assistance through the end of 2022.

6. These maps and data layers were developed to be used at a scale of approximately 1:24,000. On-the-ground field assessments are recommended for all site-specific projects.

Considerations When Interpreting the Models

- Models reflect a snapshot in time. As land use, climate patterns and other landscape changes continue to evolve, periodic updating will be needed to reflect new knowledge and current conditions.
- These maps reflect our focus on elk, mule deer, and bighorn. Though other conservation values (e.g., rare species, wetlands) have been incorporated into the Conservation and Restoration Priorities map, the needs of these ungulates have been the primary drivers of how we defined

"habitat quality." Focus on different species (e.g., birds closely tied to Pinyon-Juniper, which is a poor habitat type for ungulates) would result in a different map.

- These maps do not incorporate data from other studies being conducted concurrently with this study, but on longer timelines. Specifically, CPW's ongoing collar study for elk is expected to shed new light on how these animals actually occupy and move across the landscape. These data, when they become available in the next few years, may alter our understanding of some of the criteria we used to define habitat quality (e.g., ungulate behavioral avoidance of urbanization or recreational infrastructure). Similarly, CNHP's EPA-funded wetland study is still developing new maps for wetlands, as well as habitat suitability and occupied habitat for beaver as of this writing. We were able to incorporate preliminary wetland mapping into the Conservation Importance layer generated during this study, but new information is expected soon.
- Models are created using imperfect data. These map products are intended for regional scale planning and analysis. They should not replace on-the-ground assessment for site-specific project analysis. Data errors are more likely to be observed at scales smaller than 1:24,000.

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APPENDIX A. SCIENCE TEAM MEMBERS

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APPENDIX B. FOUNDATIONAL STUDIES AND DATA

Our general approach (targeted field sampling combined with geospatial modeling) is a well-accepted practice, but there is limited precedent in Colorado for specific methods to assess habitat quality using vegetation metrics for our focal species. Colorado Parks and Wildlife (CPW) regularly conducts census and other studies for the purpose of elk, mule deer, and bighorn herd management, but does not collect data on habitat quality. There are currently no GPS or radio collar-derived animal movement data available for the Watershed (a multi-year study is ongoing through CPW, but results are not yet available per personal communication with study lead Nathaniel Rayl). Therefore, field-derived and satellite-derived metrics were defined based on published scientific literature and reports. We relied heavily on the existing literature and data sources summarized below to develop and apply the methods presented in this report.

Monitoring Elk Nutrition and Habitat Use in Western Oregon and Washington

Rowland et al. (2018) developed a large-scale nutrition and habitat use model covering 11 million hectares in Oregon and Washington. The objectives of the study were to, "1) develop and evaluate a nutrition model that estimates regional nutritional conditions for elk on summer ranges, using predictors that reflect elk nutritional ecology; and 2) to develop a summer habitat-use model that integrates the nutrition model predictions with other covariates to estimate relative probability of use by elk, accounting for ecological processes that drive use." (p. 1-2). The study provides a nutrition-based (energy acquisition vs energy loss) framework for identifying patterns in habitat-use for free-ranging elk. Using nutrition data collected at fine scales, the authors were able to predict nutritional resources and therefore habitat use by elk across broader geographic scales. The regional habitat-use model supported by animal movement data (telemetry and GIS-collared animals) was based on four covariates: DDE (dietary digestible energy), distance to nearest road open to public use, distance to cover-forest edge, and slope. The methods and covariates selected in Rowland et al.'s regional models were used to inform covariate selection in the forage quality model and habitat quality model of this study.

Colorado Parks and Wildlife (CPW) Data and Models

Species Activity Mapping

Colorado Parks and Wildlife maintains maps of known species distributions that depict not only overall range, but also summer and winter concentration areas, severe winter range, production (e.g., calving) areas, migration corridors, and more. We used the Species Activity Maps (SAM) for elk, mule deer, and bighorn, to help guide identification of areas of critical importance to elk, mule deer, and bighorn sheep, as well as the winter versus growing season boundaries for the forage quality analysis. These maps represent on-the-ground knowledge of CPW field staff and annual herd census, as well as research study results when those are available. Maps are updated annually, but on a rolling 5-year schedule across regions (i.e., any specific region of the state is updated every five years). CPW's Northwest Region, where the Roaring Fork Watershed is located, was last updated in 2019.

Bighorn Habitat Suitability Model

In 2011, CPW biologists and GIS experts created a deductive habitat suitability model for bighorn sheep, with separate layers for summer, winter, and lambing habitat. This model was developed using animal movement data (telemetry consisting of ground very high frequency (VHF), aerial VHF, satellite, and GPS), slope, terrain ruggedness, canopy cover and vegetation (using LANDFIRE vegetation layer). It represents the knowledge of bighorn sheep in Colorado, accumulated by CPW over many years. In consultation with CPW and the Science Team, we determined that this existing model was suitable for the purposes of our study, and that additional field effort was unlikely to improve it. Therefore, rather than collecting vegetation data in the field and developing our own model, we used CPW's model as the basis for mapping habitat quality for bighorn.

The Mule Deer Habitat Quantification Tool

The Mule Deer Habitat Quantification Tool: A Multi-Scaled Approach for Assessing Impacts and Benefits to Mule Deer Habitat – Methods Document, Version 1, is authored by Anderson et al. To the authors' knowledge, this document has not yet been made available to the public. "The HQT uses a 'functional acre' approach, applied through a set of habitat attributes influencing mule deer selection of seasonal habitats across varying spatial and temporal scales" (p. 4). We used the HQT's seasonal scoring curves for shrub canopy cover to inform the tree and shrub cover scoring curves used in this study's habitat quality model. The HQT document includes a limited list of desirable forbs (n=12) and preferred shrub species (n=3) used in their models, but we consider the list too limited and with too great an emphasis on lower elevation/montane species See Appendix B for an extensive list of grasses, forbs, trees and shrubs and their associated palatability scores developed specifically for the Roaring Fork Watershed based on field observations and an extensive literature review.

Habitat Assessment Model

The Habitat Assessment Model: A Tool to Improve Wildlife Habitat Management, is authored by Wockner et al. (2009) for the Lower Colorado River with support from the Colorado Division of Wildlife through the Habitat Partnership Program (HPP). The Habitat Assessment Model (HAM) is based on the key concept that a given geography has a finite capacity for providing forage for a given array of domestic grazers (e.g., cattle, sheep, horses) and wild ungulates (e.g., elk, mule deer, bighorn sheep). "When that limit is reached or exceeded, there are ecological and animal performance consequences. The greatest dependability and the lowest risk of negative ecological and animal performance occur at moderate stocking rates that fall well below the threshold of maximum capacity." (p. 6). Model inputs include vegetation production values, wildlife winter range polygons, wild ungulate offtake from non-target species aside from elk and mule deer, and livestock offtake. Because the HAM does not account for forage quality values (i.e., the nutritional quality for wild ungulates), but rather relies on annual primary productivity estimates based on available soil survey data of variable resolutions, we opted to follow an approach similar to that of Rowland et al. (2018) for the Roaring Fork study.

Bureau of Land Management's Roaring Fork Landscape Health Assessment

The Bureau of Land Management's (BLM's) 2010 Landscape Health Assessment (DeYoung et al. 2011) was the most geographically comprehensive field-based assessment of habitat quality, albeit with an emphasis on range quality, available for the Roaring Fork Watershed prior to the completion of this study. The BLM's Landscape Health Assessment was strictly limited to the 52,564 acres of BLM managed public lands in the Watershed, which occur mainly in the lower to mid-elevations. This assessment did not use satellite-derived remote sensing data or any other means to extrapolate field observations beyond BLM lands. The BLM assessment data are now greater than a decade old, so some of the data may be less reliable if there have been changes in land use (e.g., grazing allotment status, stocking rates). However, in places without major disturbance (e.g., fire, chaining), we would expect to see little change to the vegetation over a 10-year timeframe. Thus, this assessment represents a valuable and additive dataset. We used this dataset to help us refine site selection criteria for field sampling.

Utah Division of Wildlife Resources (UDWR) Range Trend Study Methods

The UDWR conducts annual field-based monitoring to track changes in the vegetative composition of big game winter range over time based on their determination that, "the health and vigor of Utah's big game populations are closely correlated to the quality and quantity of forage in key areas." We adapted select vegetation metrics (those that could be deployed in a rapid field assessment) from this monitoring protocol for the forage quality metrics used in this study. Metrics adapted were based on UDWR's protocol for characterization of shrub availability—e.g., all available, lightly hedged (1/3 to 2/3 of plant available to animal; 0 to 40% of twigs browsed).

Normalized Difference Vegetation Index (NDVI)

Normalized Difference Vegetation Index (NDVI) is a satellite-derived vegetation index that quantifies the difference between near-infrared light which vegetation reflects and red light which vegetation absorbs. Denser, more photosynthetically active vegetation therefore produces higher NDVI values. There is a growing body of ecological research that uses NDVI as a proxy for herbivore forage quality and quantity (Christianson and Creel 2009, Hamel et al. 2009, Pettorelli et al 2011, Ryan et al. 2012), and has been tied to reproductive performance (Stoner et al. 2016) and migration ecology (Sawyer and Kaufman 2011, Middleton et al. 2013, Aikens et al. 2017) in elk and mule deer. NDVI values can be sensitive to atmospheric contamination (e.g., air moisture), exposed soil, and other confounding factors. The Atmospherically Resistant Vegetation Index (ARVI) is similar to NDVI but with corrections for atmospheric scattering effects in the red light spectrum (Kaufman and Tanré 1992). We used the ARVI to help guide sample site selection and as a satellite-derived input in the forage quality model.

APPENDIX C. TECHNICAL METHODS FOR FORAGE QUALITY MODELS (ELK AND MULE DEER)

The nutritional landscape is a critical determinant of wild ungulate population dynamics and ecology, influencing reproductive performance (Roloff 1997), health and survival (Cook et al. 1996, 2004), and migration (McNaughton 1985, Fryxell et al. 1988, Albon and Langvatn 1992, Hebblewhite et al. 2008). A significant proportion of the Roaring Fork study resources (time and funding) was dedicated to the assessment of forage quality. We use the term "forage quality" throughout this study to refer to the nutritional quality of plants and plant communities, combined with the quantity of these resources available in a given location. This focus was due primarily to the fact that forage quality (e.g., relative abundance of palatable/digestible plants vs unpalatable/undigestible plants) is difficult to assess using only remotely sensed data. Other habitat components—those that tend to be more structural by nature (e.g., deciduous shrubland vs coniferous woodland)—are more readily identified using satellite imagery and other existing data (e.g., vegetation maps).

There were four components of the forage quality assessment:

1. Field collection of data to build a forage quality model
2. Scoring of sampled sites for forage quality (High, Moderate, Low)
3. Watershed classification to extrapolate forage quality across unsampled sites
    a. Identify signatures or patterns in remotely sensed data that reflect the relative forage quality categories at the sample sites
    b. Conduct an analysis (random forest classification) to locate other areas across the watershed with comparable habitat quality signatures
4. Field sampling to test the classification model

Overview of Elk and Mule Deer Diets

Wild ungulate diets can vary in a given season due to the availability and nutritional value of forage plants and plant communities. We are unaware of any published wild ungulate forage selection studies specific to the Roaring Fork Watershed or nearby watersheds. Therefore, we used Hobbs et al.'s (1981) study on elk winter diets in Colorado, and Mower and Smith's (1989) study on elk and mule deer winter diets in Utah as references for defining forage quality in winter. We used Beck and Peek's (2005) study on mule deer, elk, cattle and sheep summer forage selection as our reference for defining forage quality during the growing season.

Winter

- Woody plants are a major component of ungulate diets during the winter, comprising 30-60% of elk and around 60% of mule deer winter diets. Elk cannot browse foliage higher than 3 m (9.8 ft); mule deer cannot browse foliage higher than 2m (6.5ft) (Armstrong et al. 2011).
- Graminoids (grasses, sedges, rushes) also comprise a significant proportion of the winter diet: 30-60% for elk and approximately 30% for mule deer.
- Forbs comprise around 6-15% of winter diet for both elk and mule deer.

Growing Season

- Forbs, especially flower heads, are critical during the summer, comprising 60-80% of summer diets for both elk and mule deer.
- Graminoids make up a smaller portion of summer diet: approximately 20-60% for elk and 5% for mule deer.
- Woody browse typically comprises 10-35% for elk, and approximately 30% for mule deer.

Wild ungulates migrate, in part, to maximize their nutritional intake of forage that varies seasonally in quality, quantity, and availability (Barker et al. 2018). However, there is a growing trend across the western United States for individuals within a population to reside on low-elevation winter range, often private agricultural land, year-round rather than migrate. This trend has been anecdotally observed over the last several decades by agricultural landowners in the Roaring Fork Valley. When wild ungulates reside on private agricultural lands year-round, conflicts can arise, including: crop damage and depredation, disease transmission to wildlife, reduced public wildlife viewing and hunting opportunities, and alteration or cessation of landscape-wide seasonal ungulate movements (Montana Fish Wildlife and Parks 2004, Idaho Department of Fish and Game 2014, Utah Division of Wildlife Resources 2015). Therefore, the focus of our forage quality analysis for the Roaring Fork study was on naturally occurring forage and native plant communities. This decision is consistent with Rowland et al.'s (2018) study on elk nutrition and habitat use in western Oregon and Washington, where agricultural and urban lands were excluded from dietary digestible energy (forage quality) models.

We acknowledge that agricultural lands can provide abundant, high quality forage (Mould & Robbins 1981, Lande et al. 2014, Barker et al. 2019), but this forage is not without the previously mentioned costs and conflicts. Additionally, we could not assume that all private agricultural landowners in the Watershed are supportive of a growing number of deer and elk in their irrigated fields and pastures year-round. Nonetheless, irrigated agriculture can have more benefits and fewer adverse impacts for wild ungulate populations than alternative forms of land use and human modification (e.g., residential and commercial development). There was considerable discussion within the Science Team about the treatment of agricultural lands, with varying opinions about the best approach, as well as varying levels of importance placed on this question. Given the fact that agricultural fields do provide some habitat, but not necessarily optimal habitat, the decision the Project and Science Teams ultimately made was to limit the forage quality model to natural ecosystems, but include agricultural lands in the habitat quality analysis (see Habitat Quality section of this report for additional information).

Field Sampling

Sampling Site Selection - 2019

Sample site selection in 2019 focused on privately owned land and was stratified to the watershed's lower and mid-elevation habitats: sagebrush, oak and mixed mountain shrublands, pinyon-juniper woodlands, and aspen woodlands. Random points were generated using the "Create Spatially Balanced Points" tool of the Geostatistical Analyst Toolbox in ESRI ArcGIS. Additional criteria were used for site selection, based in part on the BLM's Landscape Health Assessment methods (DeYoung et al. 2011) to ensure comparability and complementarity with that study. These were:

1. Number of sites scaled to the size of the private land parcels unless limited by accessibility or other factors.
2. Eliminated slopes greater than ~35% (Skovlin 1982, Ranglack et al. 2016)
3. Eliminated sites greater than 250 m from a road or 4x4 accessible trail to accommodate the need for rapid access and sampling. We acknowledge the possibility that sampling may not have been entirely representative with the elimination of remote sites. Since the focus of the 2019 field sampling was on large private properties, with much lower use/traffic on roads and trails compared to public lands, we determined that the trade-off between representativeness and ease of access was reasonable.
4. A sufficient number of sampling sites were computer-generated to provide field personnel alternate sites in case any given site proved to be inaccessible.
5. Additional sampling sites were selected by field personnel to capture plant community types that were not selected during computer-generated site selection.

Tom Cardamone (WBI) solicited and secured access to nine large (>500 acres) private landholdings available for field sampling during summer 2019. Following the receipt of signed land access agreements, field biologists coordinated directly with property contacts to determine sampling site accessibility and other field logistics.

Sampling Site Selection - 2020

Year 2 (2020) sampling focused on public land in the higher elevations of the Watershed, which included upper montane, subalpine, and alpine communities that are more characteristic of elk and mule deer transitional spring/fall and summer range. Limited sampling of the aspen ecosystem occurred in 2019, but since the sample size was small and this system is a high priority for deer and elk, we sampled additional points in mid-to-high elevation aspen stands. Site selection for the 2020 field season followed the same methods used in 2019, except:

1. Sample sites in alpine were at least 500m from roads/trails due to increased sight distances in many alpine areas, and thus increased potential for disturbance to elk and mule deer from roads and trails.
2. Sample sites in forests were at least 350m from roads/trails. This distance provided an extra 100m buffer beyond the 250m used in the landscape disturbance index (LDI) dataset[7] to account for the anthropogenic impacts of local roads, four-wheel drive trails, and hiking trails.

To ensure a geographically balanced representation of sample sites in the watershed in addition to accounting for areas of known or suspected ungulate significance, we focused on areas of the watershed where all or most of the following existed:

- Little to no CNHP sampling in 2019
- Little to no BLM sampling for the 2010 Landscape Health Assessment
- A high degree of overlap among CPW species activity map (SAM) layers for elk summer production and summer concentration areas, bighorn sheep production, summer range and winter range areas
- Large concentrations of summer NDVI values suggestive of high primary productivity corresponding to significant summer forage for all three ungulates of interest.

Elk and mule deer winter range areas were not targeted because they were foci of 2019 field assessment. Mule deer summer range areas were not included because available polygons were too large and not discrete enough to target sampling.

Data Collection Methods – 2019 and 2020

During site sampling in 2019 and 2020, we collected data on vegetation and ungulate use within 250m plots (see Appendices C and D for field forms). Vegetation metrics included:

Trees and Shrubs—percent cover class, height class, age class, and species palatability

Graminoids and Forbs—richness and percent cover

Animal Use—browse intensity, tree/shrub availability, fecal pellet counts

Plot Layout

At each sample site, two 50 m transect lines were established 90 degrees apart from the random point – hereafter referred to as the corner point (Figures C-1 and C-2). The first transect line was established in a randomly selected direction from the corner point using a random number generator smartphone app limited to select between 0 and 360 (The Random Number Generator 2013). The random number

[7] See Habitat Quality section of this report for information on the LDI.

generator app was used again to determine whether the next transect line was positioned 90 degrees above or 90 degrees below the first transect (example: Transect 1 = 267 degrees, Transect 2 = 177 degrees from corner point). Each plot represented 250 m^2 or 0.025 hectares.

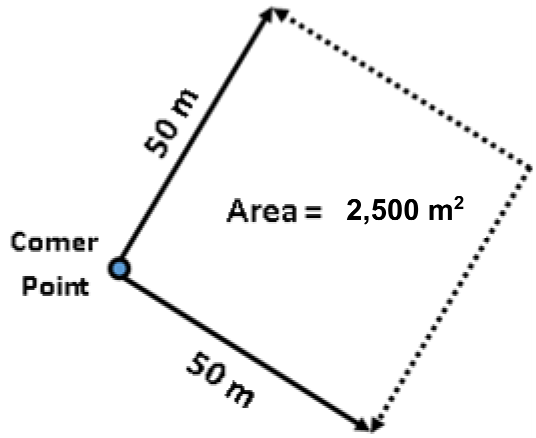

Figure C-1. Diagram of plot with established tape transect lines on two sides of the 250 m^2 plot area.

Figure C-2. Example of two transect tapes (yellow) bounding two sides of a 250 m^2 plot area. *The 90⁰ distance between each transect is distorted due to the panoramic photo view.*

Vegetation Assessment

Cover Class

Initially, vegetation cover was estimated for each plot using a modified Daubenmire (1959) ocular cover estimation procedure based on four cover classes, Class 1: 0 to 10% cover; Class 2: 10 to 25% cover; Class

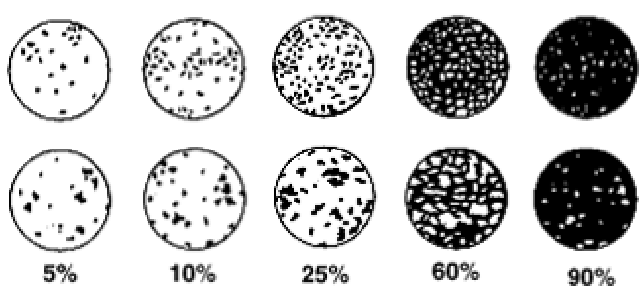

Figure C-3. Illustration of how different Daubenmire (1959) cover classes would visually appear.

3: 25 to 60% cover; and Class 4: 60 to 100% cover (Figure C-3). Daubenmire cover classes are considered semi-quantitative and regularly used in rapid assessments where "precise" estimates are not required. The vegetation cover methods were altered midway through the summer because we determined that line-point-intercept methods (BLM 1999, Figure C-4) could be used rather than cover classes without adding a prohibitive amount of time to complete each plot. Daubenmire is a preferred method for identifying species with low cover and line-point intercept is a preferred method for collecting dominate species cover. Since our interest was in the dominant species rather than uncommon species, we chose to use line-point intercept exclusively midway through the first field season and for the entire second season as it allowed for faster data collection and less observer bias. However, all cover data was utilized in the analysis, regardless of collection method, because they are comparable for common species (Floyd and Anderson 1987).

The line-point-intercept method was used along each of the 2-50 m transects in 1 m increments. Frequency counts were recorded by species for all shrubs and trees and aggregated into groups for grasses and forbs when any living plant material intercepted the transect tape from a vertical plane. Frequency counts for line-point-intercept method (29 plots) and cover class estimates (52 plots) were used to define vegetation cover for each 250 m^2 plot. Notes were made regarding the dominance or notable presence of noxious weeds and/or introduced grasses (e.g., houndstongue – *Cynoglossum vulgare,* smooth brome – *Bromus inermis,* cheatgrass – *Bromus tectorum*).

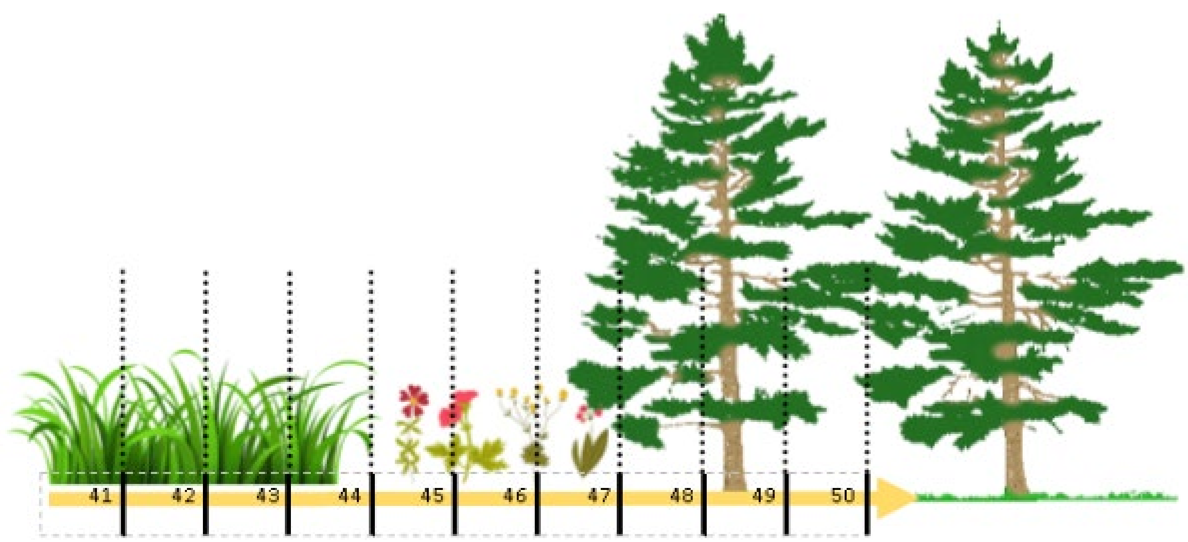

Figure C-4. Illustration of line-point-intercept method used to estimate vegetation cover. *In this example displaying a portion of a 50 m transect tape, grasses would have four hits, forbs two, and conifer species four.*

Figure C-5. Two of the study's randomly selected plot locations demonstrating the variability in herbaceous and woody plant diversity and abundance.

Height / Age Class

Shrubs and trees were characterized by height class (<0.5m; 0.5-1 m; 1-2 m; 2-3 m; and 5-10+ m) and age class (UDWR 2015):

Seedling—Up to 3 years old, firmly established, usually <1/8" diam.

Young—large w/more complex branching; usually between 1/8" - 1/4" diam.

Mature—complex branching, rounded growth, larger size, seed on healthy plants; >1/4" diam.

Decadent—plant, regardless of age, in state of decline; usually >25% dead branches

Dead

Ungulate Use

Browse Intensity and Tree/Shrub Availability

A modified Cole Browse Method (Cole 1963, BLM 1999, UDWR 2015) was used to assess intensity of ungulate utilization and the availability of shrubs and trees documented at each site (Table C-1).

Table C-1. Cole Browse classification codes modified for the purpose of this study.

Browse Code	Description
AL	All Available, little or no hedging
AM	All available, moderately hedged
AS	All available, severely hedged
PL	Partially available, little or no hedging
PM	Partially available, moderately hedged
PS	Partially available, severely hedged
UT	Unavailable due to height
UD	Unavailable due to hedging

Browse intensity, referred to as hedging, reflects how the proportion of two-year-old growth (previous year's stem leader) removed by browsing results in the current year's leader/growth to extend from terminal buds off two-year-old wood (e.g., Figure C-6). Availability is the degree to which an animal is able to access the nutritious part of forage plants. Reduced availability may be due to height of plants, density of plants (e.g., shrub thickets that are impossible to move through), or lack of new growth on plants from excessive hedging. Browsing can alter the plant's normal growth form and can ultimately result in plant decline or even mortality under severe and frequent browsing intensities. The hedging classes above are further described as follows (UDWR 2015):

Little or no hedging	Two-year-old wood is relatively long and unaltered or only slightly altered: 0 to 40 % twigs browsed.
Moderately hedged	Two-year-old wood is fairly long but most of it has been altered from the normal growth form: 41 to 60 % of twigs browsed.
Severely hedged	Two-year-old wood is relatively short and/or strongly altered from the normal growth form: >60% of twigs browsed.

Based on the intensity of browsing observed for each shrub and tree species relative to its availability, and when considering all plots in aggregate, shrubs and trees were placed into three palatability classes (Table C-2). Palatability reflects the spectrum of browse plant "preference" due to higher nutritional quality or dietary digestible energy. For example, when equally available, Mountain Mahogany (*Cercocarpus montanus*) was consistently more intensely browsed across all study plots than Snowberry (*Symphoricarpos spp*.).

*Figure C-6. Heavily browsed Gambel's oak (*Quercus gambelii*) and Mountain Mahogany (*Cercocarpus montanus*) resulting in highly altered growth form.*

Table C-2. Ungulate palatability class by shrub/tree species based on 2019 field observations and palatability score references (see also Appendix D).

Species	Common Name	Palatability Class
Symphoricarpos spp.	Snowberry	Low
Rhus spp.	Sumac	Low
Chrysothamnus/Ericameria spp.	Rabbitbrush	Low
Juniperus spp.	Juniper	Low
Pinus edulis	Pinyon Pine	Low
Populus tremuloides	Aspen	Moderate
Artemisia spp.	Sagebrush	Moderate
Quercus gambelii	Gambel's Oak	Moderate
Rosa woodsia	Rose	Moderate
Populus spp.	Cottonwood	Moderate
Prunus virginiana	Chokecherry	High
Amelanchier utahensis	Utah Serviceberry	High
Cercocarpus montanus	Mountain Mahogany	High
Purshia tridentata	Bitterbrush	High
Salix spp.	Willow	High
Cornus spp.	Dogwood	High
Alnus spp.	Alder	High

Fecal Pellet Group Count

Fecal pellet group counts provide the relative frequency and abundance of deer and elk visits to each plot (Neff 1968, Borkowski 2004, Bunnefeld et al. 2006, Thompson et al. 2011, Rogers and Mittanck 2014). In the age of more advanced animal movement data (i.e., GPS-enabled collar data), pellet group counts are still used by a variety of studies because, "pellet-group counts have been shown to provide 1) similar results for relative habitat use as measures from radio-tracking and direct observation (Leopold et al. 1984, Loft and Kie 1988, Edge and Marcum 1989) and 2) linear relationships between density estimates from pellet-group counts and other survey methods (Jordan et al. 1993)" (Mansson 2009, p. 603). Two random/wandering transects of approximately 25 m were performed in each study plot to visually count the frequency of ungulate fecal pellet groups representing a single defecation event. Each plot was given a fecal pellet group classification after averaging the observations made in each of the two transects.

The Fecal Pellet classes modified from Thompson et al. (2011) are as follows:

High – Pellets groups observed greater than 3 per 25 m transect.

Moderate – Pellet groups observed between 2-3 per 25 m transect

Low – Two or fewer pellet groups observed per 25 m transect

Additional notes regarding ungulate bedding areas, wildlife trails, etc. were made if understory vegetation was so dense that it obstructed visual observation of pellet groups (e.g., tall, dense and continuous grass/forb coverage in aspen stands). Notes were also made regarding cattle fecal piles, the presence of which indicates that observed browsing activity could be attributed to both native and domestic ungulates.

Upon further review and based on Science Team feedback, it was ultimately determined that the Fecal pellet group count metrics were too inconsistent and therefore unreliable for use in site scoring. Depending on the density of understory vegetation (e.g., lush, mesic aspen stand versus. sparsely vegetated, xeric shrubland), detection of pellet groups could vary widely. Additionally, more xeric habitats were suspected of retaining pellets for much longer periods of time (years), versus more mesic habitats, thus confounding assumptions of relative use. So, while the observation of pellet groups was useful in helping field biologists get a general feel for habitat use, these data were not considered reliable enough to include in the forage quality model.

Site Scoring Methods

We used a series of scores and modifiers based on the field data to assign categories of High, Moderate, or Low for relative forage quality for each sample site. Availability and palatability scores (Tables C-1 and C-2) were applied as modifiers to woody cover scores, as was a dense shrub cover modifier, to reflect how deer and elk might respond to woody forage present at each site. Similarly, for winter habitat, graminoid cover was modified relative to the *Bromus* dominated score to reflect the poor forage quality of cheatgrass and smooth brome. Forb and graminoid diversity (number of species in a plot) were used in winter habitat scoring (Table C-3). For growing season, percent cover modified by the palatability score for each species was used instead. Each plant species had a separate palatability score for elk and mule deer, whichever score was the highest was used in the calculations. Table C-3 shows the scoring scheme for each metric. Box 1 shows the calculations used to create the various sub-scores that go into the final Site Score.

The final Site Score for each season at each field site was then calculated by weighting each sub-score to reflect its seasonal importance, and then relativizing the scores over the maximum calculated for that season (Box 2). Each site polygon drawn by the field biologists were then assigned a classification based on the final Site Score: 2 = High, 1 = Moderate, and 0 = Low.

Table C-3. *Scoring for forage quality metrics.*

Metric	Value	Score
Graminoid Diversity	5+ species present	1
	3-4 species present	0.5
	<3 species present	0.1
Forb Diversity	11+ species present	1
	5-10 species present	0.5
	< 5 species present	0.1
Bromus dominance	Yes, dominant	0.25
	No, not dominant	1
Availability	Available	1
	Partially available	0.5
	Unavailable	0.1
Palatability	High	1
	Moderate	0.5
	Low	0.1

Box 1. Sub-score equations

1) Winter Habitat Sub-scores

$$Woody = \sum_{i=1}^{n}\left(\frac{WC_i}{100} \times \frac{(A_i + P_i)}{2}\right) \times \left(\left(\sum_{i=1}^{n} WSC_i\right) > 80 \overset{then}{\Longrightarrow} 0.25\right) \wedge (1)$$

$$Graminoid = \left(\frac{GC}{100} \times B\right) \times \left(\left(GS \geq 5 \overset{then}{\Longrightarrow} 1\right) \wedge \left(GS < 3 \overset{then}{\Longrightarrow} 0.1\right) \wedge (0.5)\right)$$

$$Forb = \left(\frac{FC}{100}\right) \times \left(\left(FS \geq 11 \overset{then}{\Longrightarrow} 1\right) \wedge \left(FS < 5 \overset{then}{\Longrightarrow} 0.1\right) \wedge (0.5)\right)$$

where: WC_i = percent cover (0-100) of the i^{th} woody species in the plot

A_i = Availability Score of the i^{th} woody species

P_i = Palatability Score of the i^{th} woody species

WSC_i = percent cover (0-100) of the i^{th} shrub species

i = each woody species documented at the plot

n = the total number of woody species at the plot

GC = percent graminoid cover (0-100) for the whole plot

GS = number of graminoid species at the plot

FC = percent forb cover (0-100) for the whole plot

FS = number of forb species at the plot

2) Growing Season Sub-scores

$$Woody = \sum_{i=1}^{n}\left(\frac{WC_i}{100} \times \frac{(A_i + P_i)}{2}\right) \times \left(\left(\sum_{i=1}^{n} WSC_i\right) > 80 \overset{then}{\Longrightarrow} 0.25\right) \wedge (1)$$

$$Graminoid = \sum_{i=1}^{n}\left(\frac{GC_i}{100} \times \max(EP_i \wedge DP_i)\right) \times B$$

$$Forb = \sum_{i=1}^{n}\left(\frac{FC_i}{100} \times \max(EP_i \wedge DP_i)\right)$$

where: GC_i = percent cover (0-100) of the i^{th} graminoid species in the plot

FC_i = percent cover (0-100) of the i^{th} forb species in the plot

EP_i = Elk palatability score

DP_i = Mule Deer palatability score

B = non-native *Bromus* species dominant score (0.25 if yes, otherwise 1)

Box 2. Final score equations

Winter Habitat final score

$$Raw\_Winter = (Woody \times 0.4) + (Graminoid \times 0.45) + (Forb \times 0.15)$$

$$Winter_{Score} = \left(\frac{Raw\_Winter}{Max(Raw\_Winter)} < 0.15 \overset{then}{\Longrightarrow} 0\right) \wedge \left(\frac{Raw\_Winter}{Max(Raw\_Winter)} > 0.3 \overset{then}{\Longrightarrow} 2\right) \wedge (1)$$

Growing Season final score

$$Raw\_GrowSeason = (Woody \times 0.1) + (Graminoid \times 0.3) + (Forb \times 0.6)$$

$$GrowSeason_{score} = \left(\frac{Raw\_GrowSeason}{Max(Raw\_GrowSeason)} < 0.15 \overset{then}{\Longrightarrow} 0\right) \wedge \left(\frac{Raw\_GrowSeason}{Max(Raw\_GrowSeason)} > 0.3 \overset{then}{\Longrightarrow} 2\right) \wedge (1)$$

Watershed Classification

Following field data collection, polygons were digitized around each field-assessed 250 m^2 plot to encompass the plant community representative of the sampling site (Figure C-7). All polygons were digitized using high resolution Google Earth imagery (Imagery: 23 June 2017) by the field biologist who sampled the site.

Figure C-7. An example of polygons digitized in Google Earth of the plant communities that are representative of each sampling site.

The classified site polygons were used to train a supervised, multi-category classification of the entire Roaring Fork watershed using the machine-learning algorithm in the R package, randomForest (Liaw and Weiner 2002). The goal of the randomForest classification process is to compare the patterns of the environmental input data that fall within each class of polygon, and then to extrapolate those patterns across the rest of the watershed. The environmental input data used is based on Sentinel-2 satellite imagery (Copernicus Sentinel data 2018-2019. DOI:10.5066/F76W992G) and a 10m resolution digital elevation model (DEM; USGS 2013).

The Sentinel-2 data used were the red, green, blue, and near-infrared 10m resolution spectral bands (bands 4, 3, 2, and 8 respectively) for May-November. June and November images were from 2019 and the rest from 2018. This date range was chosen to include the burn scar of the July through August, 2018 Lake Christine Fire north of the town of Basalt, and to cover the active growing season for the watershed. Specific days from each month were chosen based on overall image availability, quality, cloud levels, and area of coverage. The data were post-corrected to minimize atmospheric distortion using the Sen2Cor (v. 2.8) package of the European Space Agency's Sentinel Application Platform (SNAP) v. 7 (http://step.esa.int/). Cloud interference was corrected for as necessary within ESRI ArcGIS (v. 10.6.1) using imagery from similar time periods as the scenes being corrected (Fink 2020a).

In addition to the raw spectral bands, the Atmospheric Resistant Vegetation Index (ARVI) was calculated from the same set of imagery. There are multiple (conflicting) equations for ARVI in the literature (Bannari et al. 1995, EOS 2019), but we used the version described in the SNAP Sentinel-2 Toolbox and attributed to Kaufman and Tanré (1992), because this equation behaves more like the equivalent NDVI, with fewer extreme values.

$$\mathrm{ARVI} = (\mathrm{NIR} - (R - \gamma * (B - R))) \div (\mathrm{NIR} + (R - \gamma * (B - R)))$$

where R=Red band, B=Blue band, NIR=Near-infrared band, and γ=1.

The DEM was used to calculate three geomorphic metrics: Surface:Area Ratio averaged over ½ ha moving window, Landform Curvature averaged over ½ ha moving window, and a Site Exposure Index at 10m resolution. The latter two metrics were calculated using the ArcGIS Geomorphometric and Gradient Metrics Toolbox (Evans et al. 2014), but the code used for the Surface:Area Ratio was modified from that in the toolbox to produce an actual ratio.

Inputs for the models were masked in accordance with season, so that, for instance, the winter model would not attempt to evaluate areas than are normally under season-long snow cover. However, year to year variation in weather conditions means that such boundaries are not hard and fast, so the masks used for the two seasons have some overlap. For growing season, the combined elk and mule deer winter habitats as defined by the SAM maps were used to mask out winter-only habitat. For winter, a snow persistence model created by Hammond et al. (2017) was used such that areas >= 70% snow persistence were masked as growing season-only habitat.

A supervised classification is an iterative process, requiring evaluation of model performance and subsequent adjustments to the inputs (the training polygons and/or the environmental inputs) in order to minimize classification error. Multiple iterations were run using the R script available in Fink (2020b). Multiple, well-performing model runs were then combined based on their level of agreement to create the maps of elk and mule deer forage quality.

2021 Forage Quality Model Field Validation

Sampling Site Selection

The goal for the 2021 field season was to assess winter and growing season habitat within all four quadrants of the Watershed (northwest, northeast, southeast, southwest). Site assessment points were generated using the following criteria:

1. Eliminated slopes greater than ~35% (Skovlin 1982, Ranglack et al. 2016)
2. Within 500m (straight line distance) of mapped roads and trails to accommodate the need for rapid access.
3. Publicly owned to ensure field crew access without the need for special permissions.

Within these areas, an inclusion probability layer based on the inverse of model classification certainty was used so that the points were more likely to be generated in areas of higher model uncertainty. Many more points were generated than it was possible to visit, which gave field crews the ability to maximize efficiency by selecting which points to visit. Field crews also had the option to add additional assessment points opportunistically in cases where generated points proved to be inaccessible in the field. Field crews, when possible, targeted selection of point clusters around roads or trails in localized geographies representing “data gaps” (areas in the Watershed where there was limited or no field sampling in 2019 and 2020).

Model Validation Site Assessment Field Methods

Field crews navigated to a given model validation sampling site, noting the different plant communities represented within approximately 250 m of the point location. Additional points were added opportunistically if a computer-generated sampling site was inaccessible or if time allowed for adjacent, differing vegetation communities to be sampled. The 2021 field season was only a few weeks in June and early July. In order to ensure the greatest degree of geographic coverage across the Watershed, data collected at each assessment location was based on the original field sampling methods, but was adapted to dramatically reduce time spent at each site. For each point, we collected the following: site coordinates, location notes, and site description; tree/shrub cover, browse availability and palatability; forb and graminoid cover and diversity; distance to thermal hiding cover and water; presence and cover of nonnative *Bromus*; anthropogenic features within 250m radius; observed grazing impacts, ungulate use, and overall observer score. We used ocular estimates for assessing the vegetation attributes. All data were collected in the Survey 123 app on smart phones (see Appendix E for sample data form).

Model Validation Rule Set

We used the following categories to assign forage quality scores of High, Moderate, and Low to tested sites. The categories are consistent with the scoring rules for sites sampled in 2019 and 2020 used to create the classification model.

Winter Habitat

- **High Quality**
  - Not dominated by nonnative *Bromus* species

    - Plus -
  - Tree and shrub cover at least 25% where 50% or greater are palatable and available, and evidence of light to moderate browsing pressure only.

    – Or -
  - At least some tree and shrub cover is available and palatable and not severely browsed, plus forbs and graminoids have > 10% cover and forb diversity >= to 10 species and graminoid diversity >= 5 species.

- **Moderate Quality**
  - Not dominated by nonnative *Bromus* species

    - Plus –
  - All conditions not covered under High or Low Quality

- **Low Quality**
  - Dominated by nonnative *Bromus* species

    - Or -
  - No available palatable trees or shrubs

    - Or -
  - Very few available and palatable trees/shrubs, *plus* either forb richness < 5 *and* graminoid richness < 3 *or* forb cover < 10% *and* graminoid cover < 10%

Growing Season

- **High Quality**
  - Not dominated by nonnative *Bromus* species

    - Plus -
  - Either forb richness >= 21 species *or* forbs recognized as highly palatable, and *both* forb and graminoid cover > 10%

    - Or -

- Either forb cover or graminoid cover > 10%, *and* tree/shrub cover > 10% of which >= 50% are palatable and available

  - Or -
- Forb cover >= 60% and forb palatability high

- **Moderate Quality**
  - Not dominated by nonnative *Bromus* species

    - Plus -
  - All conditions not covered under High or Low Quality

- **Low Quality**
  - Dominated by nonnative *Bromus* species

    - Or -
  - Both forb and graminoid cover < 10%

    - Or -
  - Low forb palatability and low forb (<15) and graminoid (<= 3) diversity

Each visited point was converted to a 3x3 10m cell neighborhood. If any forage quality cell within this neighborhood matched the forage quality score of the point, the model agreed with the assessment. Because both field observers and the models themselves had difficulty in distinguishing Moderate from High Quality, partial matches were allowed between those two classes.

Technical Results

Of the DEM-derived metrics (e.g., Surface: Area Ratio, Landform curvature) and spectral imagery-derived metrics (e.g., red, green, blue, near-infrared, and atmospheric resistant vegetation index) used to train the multi-category classification, metrics that showed the greatest influence in predicting winter forage quality, as defined by the field data, were October ARVI, November near-infrared and the geomorphic metrics of surface: area ratio and site exposure index. For growing season forage quality, the inputs of greatest influence were May ARVI, June near-infrared and, again, surface: area ratio and site exposure.

For the winter forage quality model, 10 runs were made. Out of those, 3 were chosen as having the best outcomes (runs 3, 4, and 9). These 3 were combined to create the final forage quality model. Combining was necessary because each model had difficulty distinguishing winter-season suburban lawns and agriculture from natural forage, but in different areas as model inputs differed between runs. The Multi-class Area Under the Curve (AUC) metric for the three runs (R package pROC) were all over 0.99, with out of bag error rates of 3.7%, 3.6%, and 3.5%, respectively.

For the growing season forage quality model, 7 runs were made. Out of those, runs 3, 6, and 7 were combined to make the final model, for the same reasons as for winter. The Multi-class AUC metric for the three runs were also all over 0.99, with out of bag error rates of 1.8%, 2.2%, and 1.9%, respectively.

The very high AUC values are likely due to the large sample sizes used for each class and therefore provide little discriminatory information, other than confirming that the three classes of Low, Moderate, and High are significantly distinct from one another. Sample sizes varied between runs as a part of parameter tuning, but averaged 15,667 points per class. The AUC is only reported here because it is a commonly reported statistic of model performance and many researchers wish to know the values.

The out of bag error rates are another indication of model performance as well as input variable importance. There is no 'correct' error rate, but lower is always considered better. Anything lower than 5% is generally considered very good in terms of overall model performance.

Forty site assessment points were used for the winter forage quality model, giving an agreement score of 70% (sample size adjusted 90% confidence interval: 53% - 86%). For the growing season forage quality model, 46 assessment points were used, with an agreement of 72% (57% - 86%).

APPENDIX D. PALATABILITY SCORES FOR FORAGE SPECIES

We reviewed all the reports and publications we were able to find that included information on elk and deer forage. The best sources are listed under References section if this Appendix[8]. Some of our resources described food plants in terms of "palatability," while others described food plants in terms of "forage quality." Some studies referencing forage quality included the nutritional value, but overall very few studies have included nutritional values. We chose to use "palatability" to describe the food plants utilized. In general, shrubs have a lower nutritional value than forbs and grasses, but they are an important part of elk and deer winter forage.

Elk and deer have some overlap in diet, but in general, elk eat a larger variety of plants and at times, grasses can be an important component, whereas deer eat fewer species than elk and seldom utilize grasses/graminoids in significant proportions.

We scored plant species for palatability as High (consumed to a high degree), Moderate (consumed to a moderate degree), or Low (consumed to a small degree or not at all). When a species had a different palatability score for deer vs elk, we used the highest score in our forage quality model to ensure that the highest resource value was represented, as these two species were not separated in our forage quality model. We recognize that deer and elk eat different species during each season, with winter consisting of the fewest number of different species and summer the highest. When species had a different palatability score for winter vs summer, we chose the highest score.

We scored 131 species as being utilized by elk, of which 73 were highly palatable and 58 moderately palatable. For deer, we scored 119 species, of which 53 were highly palatable and 66 moderately palatable. Most of these species occur in the growing season range rather than the winter range. See Table B-1 for scores by species.

Note that common names are not standardized for plant species. Most plants have multiple common names, and there is no consistency for when or how those names are used. Therefore, we have relied on scientific names in the following table.

[8] Two of these references, Johnston et al. 2001 and FEIS website cited additional literature, which is not included in the Reference list.

Table B-1. Palatability scores. High (H) = consumed to a high degree; Moderate (M) = consumed only to a moderate degree; Low (L) = consumed to a small degree or not at all. This list is sorted by habit, then by scientific name.

Scientific Name	**Habit**	**Elk**	**Deer**
Antennaria	Forb	L	M
Achillea millefolium	Forb	L	L
Aconitum columbianum	Forb	H	H
Agastache uticifolia	Forb	M	M
Agoseris aurantiaca	Forb	M	M
Agoseris glauca	Forb	H	M
Anaphalis margaritacea	Forb	L	L
Anemone canadensis	Forb	H	H
Anemone multifida	Forb	H	H
Anemone narcissiflora	Forb	H	H
Anemone parviflora	Forb	H	H
Angelica grayi	Forb	ND	ND
Antennaria parvifolia	Forb	L	M
Antennaria rosea	Forb	L	M
Antilclea elegans	Forb	M	ND
Aquilegia coerulea	Forb	ND	ND
Arabis drummondii	Forb	ND	ND
Arnica cordifolia	Forb	H	H
Arnica mollis	Forb	H	H
Artemesia ludoviciana	Forb	M	M
Artemisia dracunculus	Forb	M	M
Artemisia frigida	Forb	M	L
Artemisia scopulorum	Forb	L	L
Aster	Forb	M	H
Aster alpinus	Forb	ND	ND
Astragalus	Forb	H	M
Balsamorhiza sagittata	Forb	M	H
Calochortus gunnisonii	Forb	ND	ND
Caltha leptosepala	Forb	H	H
Campanula rotundifolia	Forb	ND	ND
Capsella bursa	Forb	ND	ND
Cardamine cordifolia	Forb	M	M
Carduus	Forb	ND	ND
Castilleja	Forb	L	L
Castilleja integra	Forb	ND	ND
Castilleja occidentalis	Forb	ND	ND
Castilleja rhexiifolia	Forb	ND	ND
Castilleja sulphurea	Forb	L	L

Scientific Name	**Habit**	**Elk**	**Deer**
Chamerion angustifolium	Forb	H	H
Chenopodium	Forb	ND	ND
Chimaphila umbellata	Forb	M	L
Chlorocrepis triste	Forb	ND	ND
Cirsium	Forb	L	M
Cirsium arvense	Forb	L	ND
Cirsium eatonii	Forb	ND	ND
Cirsium osterhoutii	Forb	ND	ND
Cirsium scariosum	Forb	ND	ND
Cirsium scariosum	Forb	H	ND
Cirsium vulgare	Forb	ND	ND
Clematis ligusticifolia	Forb	ND	M
Collomia linearis	Forb	L	L
Comandra umbellata	Forb	M	M
Conioselinum scopulorum	Forb	H	H
Conium maculatum	Forb	ND	ND
Cryptantha sericea	Forb	ND	L
Cymopterus alpinus	Forb	H	ND
Cymopterus montanus	Forb	H	H
Cynoglossum officinale	Forb	ND	ND
Delphinium barbeyi	Forb	M	M
Delphinium nuttallianum	Forb	M	M
Dodecatheon pulchellum	Forb	L	ND
Draba	Forb	ND	ND
Epilobium	Forb	ND	ND
Epilobium anagallidifolium	Forb	ND	ND
Erigeron coulteri	Forb	M	L
Erigeron elatior	Forb	ND	ND
Erigeron flagellaris	Forb	ND	M
Erigeron glabellus	Forb	ND	ND
Erigeron glacialis	Forb	ND	ND
Erigeron grandiflorus	Forb	ND	ND
Erigeron melanocephalus	Forb	L	L
Erigeron peregrinus	Forb	H	H
Erigeron pinnatisectus	Forb	L	L
Erigeron simplex	Forb	ND	ND
Erigeron speciosus	Forb	M	M
Erigeron vetensis	Forb	ND	ND
Eriogonum umbellatum	Forb	M	H
Erodium cicutarium	Forb	ND	L

Scientific Name	**Habit**	**Elk**	**Deer**
Erythronium grandiflorum	Forb	H	H
Erythronium grandiflorum	Forb	ND	ND
Eucephalus engelmannii	Forb	H	H
Fragaria	Forb	M	H
Fragaria virginiana	Forb	M	M
Frasera speciosa	Forb	ND	ND
Galium	Forb	ND	ND
Galium boreale	Forb	L	M
Galium trifidum	Forb	ND	ND
Gallardia	Forb	ND	L
Gayophytum racemosum	Forb	ND	ND
Gentiana	Forb	ND	ND
Gentiana parryi	Forb	ND	ND
Gentianella amarella	Forb	ND	ND
Geranium richardsonii	Forb	H	H
Geranium viscosissimum	Forb	H	H
Geum macrophyllum	Forb	ND	ND
Geum rossii	Forb	M	ND
Geum triflorum	Forb	M	ND
Glycyrrhiza lepidota	Forb	H	ND
Helenium autumnale	Forb	L	L
Helianthella	Forb	ND	ND
Helianthella quinquenervis	Forb	H	H
Helianthus	Forb	ND	ND
Helianthus maximiliani	Forb	ND	ND
Heliomeris multiflora	Forb	ND	ND
Heracleum maximum	Forb	H	H
Hieracium albiflorum	Forb	ND	ND
Hieracium albiflorum	Forb	M	ND
Hieracium gracile	Forb	ND	ND
Hydrophyllum capitatum	Forb	H	ND
Hymenopappus filifolius	Forb	ND	L
Hymenoxis grandiflora	Forb	L	ND
Hymenoxys hoopesii	Forb	ND	ND
Iliamna rivularis	Forb	H	ND
Ipomopsis aggregata	Forb	ND	ND
Iris misouriensis	Forb	L	ND
Lactuca serriola	Forb	M	ND
Lathyrus lanszwertii	Forb	H	H
Lewisia pygmaea	Forb	M	ND

Scientific Name	**Habit**	**Elk**	**Deer**
Liatris punctata	Forb	H	ND
Ligusticum filicinum	Forb	M	ND
Ligusticum porteri	Forb	H	H
Ligusticum tenuifolium	Forb	M	M
Linum lewesii	Forb	L	L
Lupinus	Forb	M	ND
Lupinus argenteus	Forb	H	H
Lupinus bakeri	Forb	H	H
Lupinus caudatus	Forb	ND	L
Lupinus sericeus	Forb	H	ND
Maianthemum racemosum	Forb	M	H
Maianthemum stellatum	Forb	M	H
Medicago sativa	Forb	H	ND
Melilotus officinalis	Forb	H	ND
Menyanthes trifoliata	Forb	ND	ND
Mertensia alpina	Forb	ND	ND
Mertensia ciliata	Forb	H	H
Mertensia lanceolata	Forb	ND	L
Mimulus guttatus	Forb	ND	ND
Monarda	Forb	ND	L
Musineon divaricatum	Forb	H	ND
Noccaea fendleri	Forb	ND	ND
Oreochrysum parryi	Forb	M	H
Orobanche broomrape	Forb	ND	ND
Orobanche fasciculata	Forb	ND	ND
Orthilia secunda	Forb	L	L
Osmorhiza depauperata	Forb	H	H
Osmorhiza occidentalis	Forb	H	H
Oxypolis fendleri	Forb	H	H
Oxyria digyna	Forb	M	ND
Oxytropis campestris	Forb	M	ND
Oxytropis lambertii	Forb	L	ND
Packera pseudaurea	Forb	ND	ND
Packera ragwort	Forb	ND	ND
Paronychia pulvinata	Forb	ND	ND
Pedicularis bracteosa	Forb	H	H
Pedicularis groenlandica	Forb	M	L
Pedicularis procera	Forb	ND	ND
Pedicularis racemosa	Forb	H	H
Penstemon whippleanus	Forb	ND	ND

Scientific Name	**Habit**	**Elk**	**Deer**
Phacelia hastata	Forb	M	ND
Phlox hoodii	Forb	L	L
Platanthera	Forb	ND	ND
Polemonium caeruleum	Forb	H	ND
Polemonium pulcherrimum	Forb	M	L
Polygonum bistortoides	Forb	M	M
Polygonum douglasii	Forb	L	L
Polygonum viviparum	Forb	M	M
Potentilla	Forb	L	ND
Potentilla arguta	Forb	ND	ND
Potentilla concinna	Forb	ND	ND
Potentilla diversifolia	Forb	H	ND
Potentilla glandulosa	Forb	M	ND
Potentilla gracilis	Forb	L	ND
Potentilla pulcherrima	Forb	ND	ND
Potentilla subjuga	Forb	ND	ND
Primula parryi	Forb	ND	ND
Pseudocymopterus montanus	Forb	L	M
Pteridium aquilinum	Forb	L	ND
Pyrola minor	Forb	H	ND
Pyrola picta	Forb	H	ND
Ranunculus alismifolius	Forb	ND	ND
Ranunculus glaberrimus	Forb	L	ND
Rhodiola integrifolia	Forb	L	L
Rhodiola rhodantha	Forb	L	ND
Rubus deliciosus	Forb	ND	L
Rudbeckia laciniata	Forb	L	M
Rumex crispus	Forb	ND	ND
Saxifraga flagellaris	Forb	ND	ND
Saxifraga odontoloma	Forb	ND	ND
Saxifraga oregana	Forb	ND	ND
Saxifraga rhomboidea	Forb	ND	ND
Saxifraga saxifrage	Forb	ND	ND
Scrophularia lanceolata	Forb	ND	ND
Sedum lanceolatum	Forb	ND	ND
Senecio amplectens	Forb	H	H
Senecio crassulus	Forb	M	M
Senecio fremontii	Forb	ND	ND
Senecio mutabilis	Forb	ND	L
Senecio serra	Forb	M	M

Scientific Name	**Habit**	**Elk**	**Deer**
Senecio soldanella	Forb	ND	ND
Senecio triangularis	Forb	H	H
Sibbaldia procumbens	Forb	ND	ND
Silene acaulis	Forb	ND	ND
Solidago goldenrod	Forb	ND	ND
Solidago multiradiata	Forb	L	M
Solidago nana	Forb	ND	ND
Solidago simplex	Forb	ND	ND
Solidago velutina	Forb	ND	ND
Sonchus arvensis	Forb	M	ND
Swertia perennis	Forb	ND	ND
Symphyotrichum foliaceum	Forb	M	M
Symphyotrichum laeve	Forb	M	M
Taraxacum officinale	Forb	M	M
Tetraneuris grandiflora	Forb	ND	ND
Thalictrum alpinum	Forb	L	L
Thalictrum fendleri	Forb	M	M
Thermopsis montana	Forb	L	ND
Tonestus pygmaeus	Forb	ND	ND
Tragopogon dubius	Forb	M	ND
Trifolium	Forb	H	ND
Trifolium dasyphyllum	Forb	H	H
Trifolium haydenii	Forb	M	ND
Trifolium nanum	Forb	H	H
Trifolium repens	Forb	H	ND
Trillium ovatum	Forb	ND	ND
Typha	Forb	L	ND
Valeriana edulis	Forb	H	H
Valeriana occidentalis	Forb	L	L
Veratrum tenuipetalum	Forb	L	ND
Veronica	Forb	ND	ND
Veronica wormskjoldii	Forb	ND	ND
Vicia americana	Forb	M	L
Viola	Forb	M	ND
Viola canadensis	Forb	M	ND
Viola nephrophylla	Forb	M	ND
Wethia	Forb	H	ND
Xanthium strumarium	Forb	H	ND
Zigadenus elegans	Forb	M	ND
Achnatherum hymenoides	Graminoid	H	M

Scientific Name	**Habit**	**Elk**	**Deer**
Achnatherum lettermanii	Graminoid	H	M
Achnatherum nelsonii	Graminoid	H	L
Achnatherum robustum	Graminoid	L	L
Agropyron cristatum	Graminoid	M	L
Agrostis	Graminoid	M	ND
Agrostis gigantea	Graminoid	H	L
Alopecurus magellanicus	Graminoid	L	L
Alopecurus pratensis	Graminoid	M	L
Aristida purpurea	Graminoid	L	L
Bouteloua curtipendula	Graminoid	H	L
Bouteloua gracilis	Graminoid	H	L
Bromus carinatus	Graminoid	H	M
Bromus ciliatus	Graminoid	H	M
Bromus marginatus	Graminoid	H	ND
Bromus porteri	Graminoid	H	M
Bromus pubescens	Graminoid	ND	ND
Bromus sp	Graminoid	H	ND
Broumus inermis	Graminoid	M	M
Broumus tectorum	Graminoid	M	H
Calamagrostis canadensis	Graminoid	H	M
Calamagrostis purpurascens	Graminoid	H	M
Carex	Graminoid	H	ND
Carex aquatilis	Graminoid	H	L
Carex canescens	Graminoid	M	ND
Carex ebenea	Graminoid	H	L
Carex filifolia	Graminoid	H	ND
Carex geyeri	Graminoid	H	L
Carex haydeniana	Graminoid	M	ND
Carex interior	Graminoid	H	L
Carex microptera	Graminoid	ND	ND
Carex nigricans	Graminoid	H	L
Carex occidentalis	Graminoid	ND	ND
Carex raynoldsii	Graminoid	M	ND
Carex saxatilis	Graminoid	H	L
Carex sedge	Graminoid	H	L
Carex utriculata	Graminoid	H	H
Dactylis	Graminoid	M	ND
Dactylis glomerata	Graminoid	M	M
Danthonia intermedia	Graminoid	H	ND
Danthonia parryii	Graminoid	H	ND

Scientific Name	**Habit**	**Elk**	**Deer**
Deschampsia cespitosa	Graminoid	H	M
Distichlis spicata	Graminoid	M	ND
Eleocharis	Graminoid	ND	ND
Elymus	Graminoid	ND	ND
Elymus canadensis	Graminoid	M	L
Elymus cinerus	Graminoid	ND	ND
Elymus elymoides	Graminoid	L	M
Elymus glaucus	Graminoid	H	M
Elymus lanceolatus	Graminoid	L	ND
Elymus repens	Graminoid	L	L
Elymus scribneri	Graminoid	M	ND
Elymus trachycaulus	Graminoid	H	M
Equisetum arvense	Graminoid	L	L
Eriophorum cottongrass	Graminoid	ND	ND
Festuca	Graminoid	ND	ND
Festuca idahoensis	Graminoid	H	M
Festuca thurberi	Graminoid	H	M
Glyceria	Graminoid	ND	ND
Glyceria mannagrass	Graminoid	ND	ND
Hesperostipa comata	Graminoid	M	M
Juncus	Graminoid	M	ND
Juncus arcticus	Graminoid	H	M
Juncus drummondii	Graminoid	M	L
Juncus dudleyi	Graminoid	M	L
Juncus mertensianus	Graminoid	M	L
Juncus parryi	Graminoid	H	ND
Kobresia	Graminoid	H	ND
Kobresia simpliciuscula	Graminoid	H	L
Koelaria micrantha	Graminoid	H	ND
Leucopoa kingii	Graminoid	M	ND
Luzula parviflora	Graminoid	H	ND
Melica	Graminoid	H	H
Melica bulbosa	Graminoid	H	H
Melica spectbilis	Graminoid	M	ND
Melica subulata	Graminoid	L	ND
Muhlenbergia filiformis	Graminoid	M	ND
Muhlenbergia montana	Graminoid	L	ND
Nassella viridula	Graminoid	M	ND
Panicum	Graminoid	M	ND
Pascopyrum smithii	Graminoid	H	L

Scientific Name	**Habit**	**Elk**	**Deer**
Phalaris arundinaceae	Graminoid	H	L
Phleum alpinum	Graminoid	H	H
Phleum pratense	Graminoid	M	M
Poa	Graminoid	M	ND
Poa alpina	Graminoid	M	L
Poa arctica	Graminoid	M	ND
Poa bulbosa	Graminoid	M	ND
Poa compressa	Graminoid	H	ND
Poa cusickii	Graminoid	M	ND
Poa fendleriana	Graminoid	H	M
Poa palustris	Graminoid	M	ND
Poa pratensis	Graminoid	M	M
Poa secunda	Graminoid	M	ND
Pseudorogneria spicata	Graminoid	H	ND
Purple grass	Graminoid	ND	ND
Thinopyrum intermedium	Graminoid	M	ND
Trisetum spicatum	Graminoid	H	M
Trisetum wolfii	Graminoid	M	L
Vahlodea atropurpurea	Graminoid	L	L
Eragrostis spectabilis	Graminoid	ND	ND
Acer glabrum	Shrub	M	ND
Alnus incana	Shrub	M	M
Amelanchier utahensis	Shrub	H	H
Arctostaphylos uva	Shrub	M	M
Artemisia tridentata	Shrub	M	H
Betula glandulosa	Shrub	H	M
Ceanothus velutinus	Shrub	H	H
Cercocarpus montanus	Shrub	H	H
Chrysothamnus depressus	Shrub	L	L
Chrysothamnus viscidiflorus	Shrub	L	L
Cornus sericea	Shrub	H	H
Dasiphora fruticosa	Shrub	L	L
Ericameria nauseosa	Shrub	L	L
Heterotheca villosa	Shrub	L	L
Holodiscus dumosus	Shrub	M	ND
Juniperus communis	Shrub	L	M
Kalmia microphylla	Shrub	L	L
Krascheninnikovia lanata	Shrub	M	H
Lonicera involucrata	Shrub	M	M
Mahonia repens	Shrub	M	H

Scientific Name	**Habit**	**Elk**	**Deer**
Paxistima myrsinites	Shrub	M	ND
Physocarpus malvaceus	Shrub	ND	H
Prunus virginiana	Shrub	H	H
Purshia tridentata	Shrub	H	H
Quercus gambelii	Shrub	H	H
Ribes	Shrub	L	ND
Ribes cereum	Shrub	H	H
Ribes montigenum	Shrub	H	M
Rosa woodsii	Shrub	M	L
Rubus idaeus	Shrub	M	M
Rubus parviflorus	Shrub	M	M
Salix	Shrub	M	H
Salix bebbiana	Shrub	H	H
Salix brachycarpa	Shrub	M	M
Salix drummondiana	Shrub	M	ND
Salix exigua	Shrub	M	ND
Salix geyeriana	Shrub	M	H
Salix glauca	Shrub	M	M
Salix lucida	Shrub	H	H
Salix lutea	Shrub	H	ND
Salix nivalis	Shrub	ND	ND
Salix planifolia	Shrub	H	H
Salix scouleriana	Shrub	M	ND
Sambucus racemosa	Shrub	H	H
Sheperdia canadensis	Shrub	H	ND
Symphoricarpos rotundifolius	Shrub	L	L
Tetradymia canescens	Shrub	ND	L
Vaccinium	Shrub	M	H
Vaccinium cespitosum	Shrub	M	H
Vaccinium myrtillus	Shrub	M	H
Vaccinium scoparium	Shrub	M	H
Abies lasiocarpa	Tree	L	L
Juniperus osteosperma	Tree	L	L
Juniperus scopulorum	Tree	L	L
Picea engelmannii	Tree	L	L
Picea pungens	Tree	L	L
Pinus contorta	Tree	L	L
Pinus edulis	Tree	L	L
Populus tremuloides	Tree	M	H
Pseudotsuga menziesii	Tree	L	L

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APPENDIX E. 2019 SAMPLING FIELD FORM

ROARING FORK ECOLOGICAL SITE ASSESSMENT

IDENTIFIERS/LOCATORS

Plot/Photo ID/GPS FILE: ________________________ Visit Date:____________________ Visit Time______________________

Observers:____

UTM X___ ___ ___ ___ ___ ___ UTM Y ___ ___ ___ ___ ___ ___ ___ +/- ____m Photo Points Taken for Transects: Y / N

Land Cover Community Type: ____

Public Landowner : __________________________________ Property Name: ______________________________________

Private Landowner Name: ____ Phone: _________________________

Private Landowner Address:____ Signed Access Form: Y / N

PLOT DESCRIPTION

Plot Directions/Description:	Physiognomic Class (check all that apply):
	___ Forest/Woodland
	___ Shrubland
	___ Grassland/Meadow
	___ Sparsely Vegetated
	___ Wetland/Riparian
	___ Pasture
	___ Other: ___________________________
	Landscape Position:
	____ Summit/Ridgetop
	____ Riparian/Floodplain
Transect 1: 50m at _________ degrees	____ Slope/Hillside
Transect 2: 50m at _________ degrees	____ Terrace

VEGETATION DESCRIPTION

Unvegetated Cover Class:	Unvegetated Surface:
01 = 0 –10%	______ Rock
02 = 10 - 25%	______ Sand
03 = 25-60%	______ Bare Soil
04 = 60-100%	______ Litter/Duff
	______ Downed Wood

	Densiometer Reading	
Transect	0m	50m
1		
2		

Page 1 of 5

Date: ____________ Plot ID: ____________

VEGETATIVE STRUCTURE/COMPOSITION					
Species	Cover Class (Live)	Height Class	Tree DBH Class	Shrub Class	Browse Code

Cover Class:

01: 0-10%

02: 10-25%

03: 25-60%

04: 60-100%

Height Class:

01: <0.5m

02: 0.5-1m

03: 1-2m

04: 2-5m

05: 5-10+m

Tree DBH Class:

01: 1—5 inches

02: 6—15 inches

03: 16—25 inches

04: 26+ inches

Shrub Class:

S: Seedling—Up to 3 yro, firmly established, usually <1/8" diam.

Y: Young—large w/more complex branching; usually between 1/8" - 1/4" diam.

M: Mature—complex branching, rounded growth, larger size, seed on healthy plants; >1/4" diam.

D: Decadent—plant, regardless of age, in state of decline; usually >25% dead branches

X: Dead

Browse Code:

AL: all available, little or no hedging

AM: all available, moderately hedged

AS: all available, severely hedged

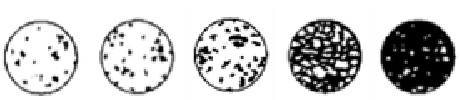
PL: partially available, little or no hedging

PM: partially available, moderately hedged

PS: partially available, severely hedged

UT: Unavailable due to height

UD: Unavailable due to hedging



5% 10% 25% 60% 90%

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Date: ____________ Plot ID: ____________

BIOTIC INTEGRITY EVALUATION

Wildlife use, livestock use (intensity and season of allotted use), and recent disturbances:

____

____

____

____

Off-site influences on evaluation criteria:

____

____

____

____

Condition relative to Reference (e.g., reduced clump grass cover):

____

____

____

____

Other:

____

____

____

____

LAND USE CHECKLIST

Land Use	Scope	Impact
Residential, recreational buildings, associated pavement		
Industrial, commercial, military buildings, associated pavement		
Oil and gas wells and surrounding footprint		
Roads (dirt =1, gravel =2, paved =3, highway =4)		
Row-crop agriculture, orchard, nursery		
Hay field, pasture		
Utility/power line corridor		
Low impact recreation (hunting, fishing, camping, hiking, canoe/ kayaking, bird watching)		
High impact recreation (ATV, mountain biking, motor boats, horseback riding)		
Livestock grazing		
Invasive/Noxious Species		
Irrigation ditches, canals and other infrastructure (e.g., pipes)		

Scope of Land Use (% of Plot or landscape affected by land use)	
1 = Small	Affects a small portion (1-10%) of the Plot or landscape
2 = Restricted	Affects some (11-30%) of the Plot or landscape
3 = Large	Affects much (31-70%) of the Plot or landscape
4 = Pervasive	Affects all or most (71-100%) of the Plot or landscape
Impact within the defined Scope (degree of impact within Plot)	
1 = Slight	Likely to only slightly degrade/reduce
2 = Moderate	Likely to moderately degrade/reduce
3 = Serious	Likely to seriously degrade/reduce
4 = Extreme	Likely to extremely degrade/destroy or eliminate

Landscape defined by 500m radius surrounding Plot

Page 3 of 5

Date: ____________ Plot ID: ____________

Functional/Structural Groups			Species List for Functional/Structural Groups
Name	Potential	Actual	Plant Names
Noxious Weeds			
Invasive Plants			

Indicate whether each "structural/functional group" is a Dominant (D) (roughly 40%-100% composition), a **Sub-dominant (S)** (roughly 10-40% composition), a **Minor Component (M)** (roughly 2-10% composition), or a **Trace Component (T)** (<2% composition) based on weight or cover composition in the area of interest (e.g., "Actual" column) relative to the "Potential" column derived from information found in the ecological site/description and/or at the ecological reference area.

Page 4 of 5

Date: ____________ Plot ID: ____________

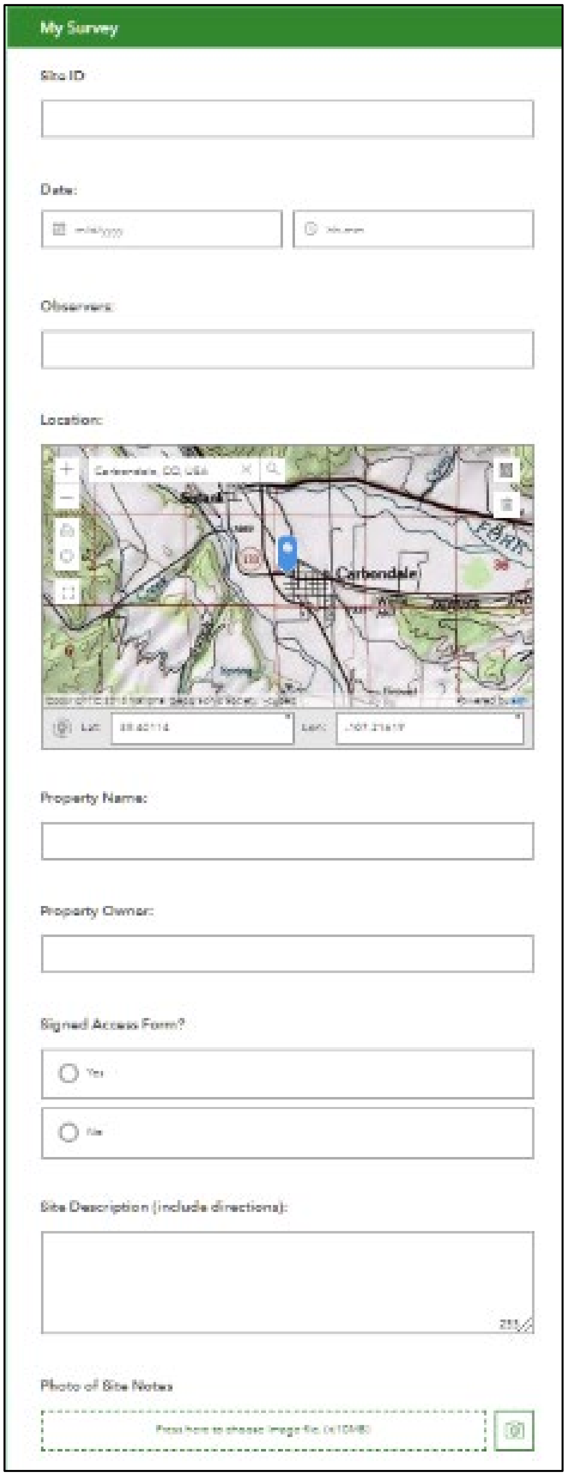
PLANT SPECIES LIST

FORB/GRASSES	Browsed/Grazed? (check)

TREES/SHRUBS	Browsed/Grazed? (check)

APPENDIX F. SURVEY123 FORM USED FOR 2020 FIELD SAMPLING

Screenshot examples of Survey123 forms used on field staff's iPhones to collect site data. A table of collected metrics used to create the Survey123 forms follows.



My Survey

Site ID

Date:

Observers:

Location:

Property Name:

Property Owner:

Signed Access Form?

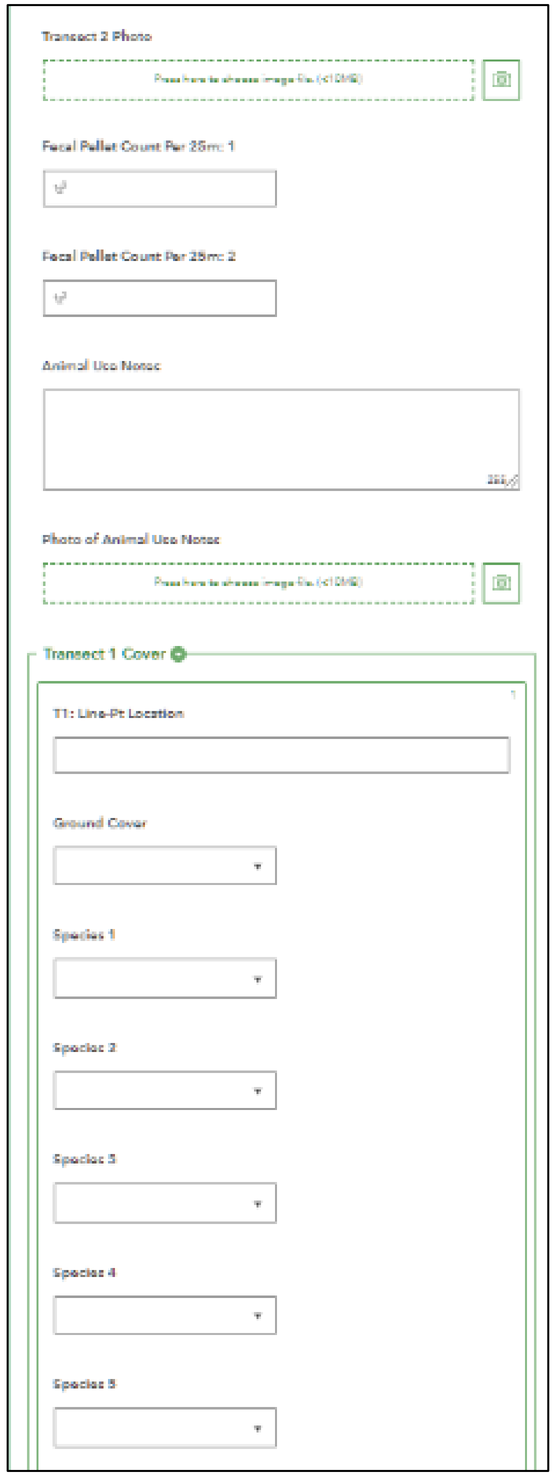
Yes

No

Site Description (include directions):

Photo of Site Notes

Press here to choose image file. (<10MB)



Transect 2 Photo

Press here to choose image file. (<10MB)

Fecal Pellet Count Per 25m: 1

Fecal Pellet Count Per 25m: 2

Animal Use Notes

Photo of Animal Use Notes

Press here to choose image file. (<10MB)

Transect 1 Cover

T1: Line-Pt Location

Ground Cover

Species 1

Species 2

Species 3

Species 4

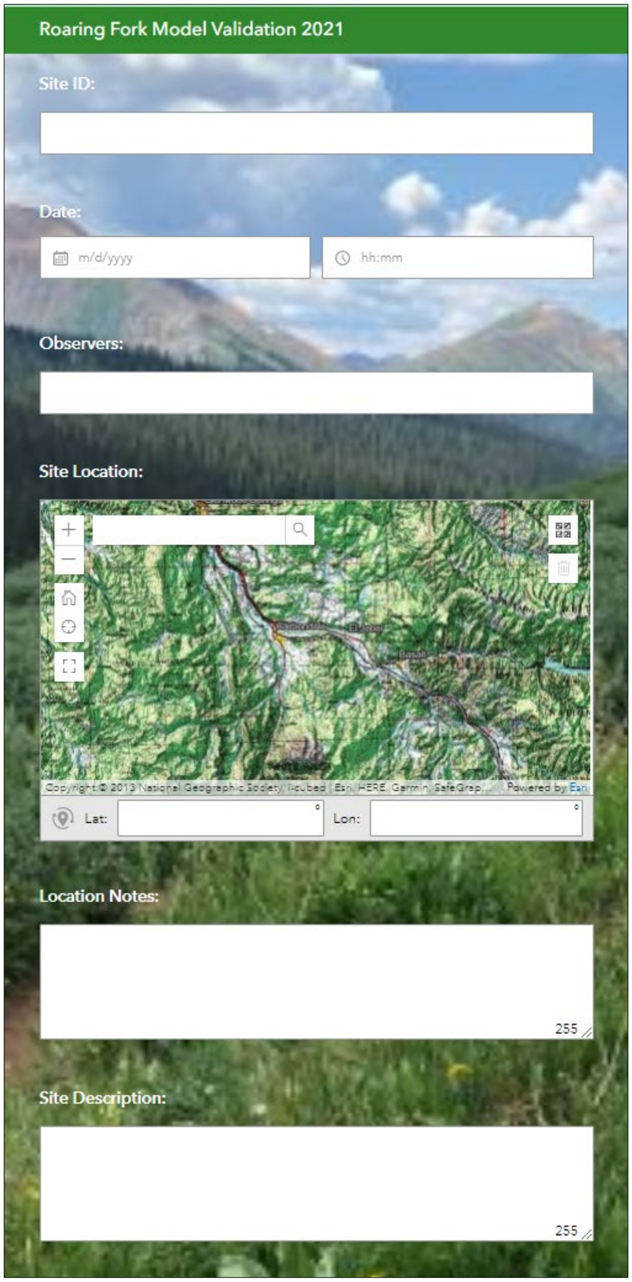
Species 5

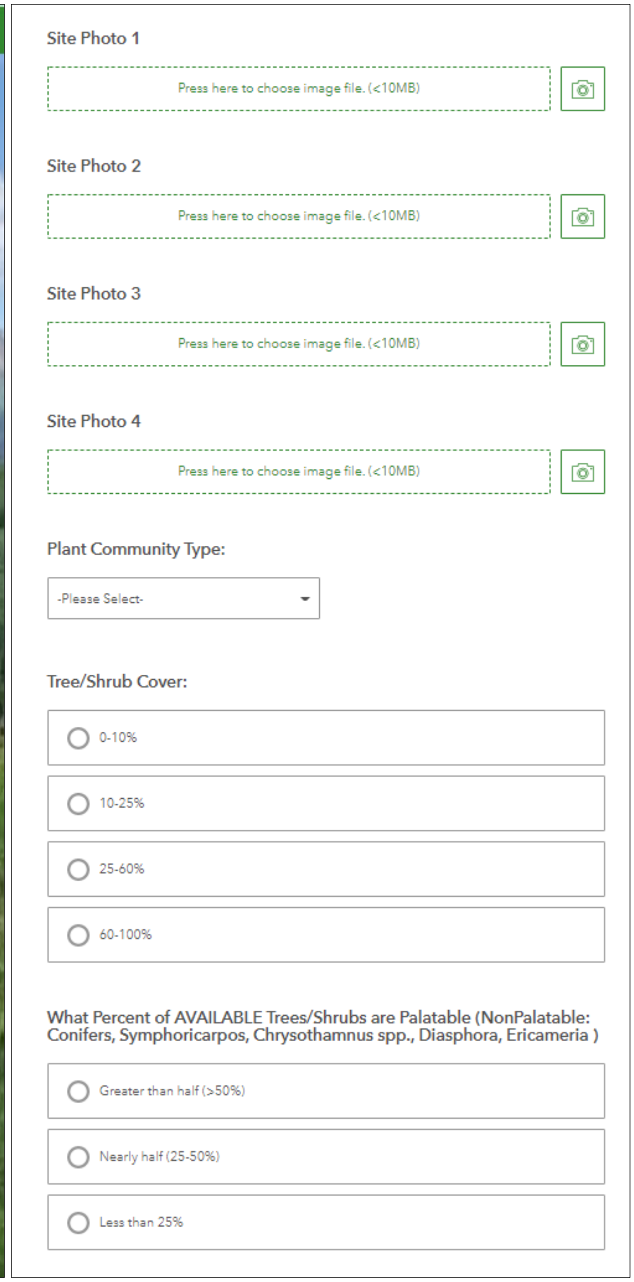
Forage Quality Habitat Assessment Metrics
Site Description
Site ID -> *open entry*
Date -> *open entry*
Observers -> *open entry*
Location -> *geolocation*
Property Name -> *open entry*
Property Owner -> *open entry*
Signed Access Form -> *open entry*
Site Description (include directions) -> *open entry*
Photo of Site Notes-> *image file*
Directional Degrees: Transect 1 -> *open entry*
Directional Degrees: Transect 2 -> *open entry*
Transect 1 Photo-> *image file*
Transect 2 Photo-> *image file*
Fecal Pellet Count Per 25m: Transect 1 -> *open entry*
Fecal Pellet Count Per 25m: Transect 2 -> *open entry*
Animal Use Notes -> *open entry*
Photo of Animal Use Notes
Transect 1 Cover
T1: Line-Point Location -> *geolocation*
Ground Cover -> *select one*: bare soil; rock; sand; litter/duff; snow; water; downed wood
Species 1 -> *select one* among 5519 possible species described for Colorado as per USDA Plants Database
Species 2 -> *same as above*
…
Species 5 -> *same as above*
Uncoded Species -> *open entry* for species or synonyms not included in USDA Plants Database
T2…T50 -> *repeat the above* for all 50 line-point-intercept locations along the 50m line
Transect 2 Cover
T1: Line-Point Location -> *geolocation*
Ground Cover -> *select one*: bare soil; rock; sand; litter/duff; snow; water; downed wood
Species 1 -> *select one* among 5519 possible species described for Colorado as per USDA Plants Database
Species 2 -> *same as above*
…
Species 5 -> *same as above*
Uncoded Species -> *open entry* for species or synonyms not included in USDA Plants Database
T2…T50 -> *repeat the above* for all 50 line-point-intercept locations along the 50m line
Woody Characterization (the following is recorded for each available shrub species)
Tree/Shrub Species -> *select one* among 5519 possible species described for Colorado as per USDA Plants Database
For above selected species

Forage Quality Habitat Assessment Metrics
Height Class -> *select one*: <0.5m; 0.5 to 1m; 1 to 2m; 2 to 5m; 5 to 10m
Tree DBH-> *select one*: 1 to 5 in; 6 to 15 in; 16 to 25 in; 25+ in
Shrub Age Class -> *select one*:
Seedling: up to 3 yro, firmly established, usually < 1/8” diameter
Young: large w/more complex branching, usually between 1/8”-1/4” diameter
Mature: complex branching, rounded growth, larger size, seed on healthy plants, >1/4" diameter
Decadent: plant, regardless of age, in state of decline, usually > 25% dead branches
Dead
Browse Code -> *select one*:
AL: all available, little or no hedging
AM: all available, moderately hedged
AS: all available, severly hedged
PL: partially available, little or no hedging
PM: partially available, moderately hedged
PS: partially available, severely hedged
UT: unavailable due to height
UD: unavailable due to hedging
Site Score and Justification
Observer Score-> *select one*:
Excellent Quality
Good Quality
Moderate Quality
Poor Quality
Not Habitat
Observer Score Justification-> *open entry*

APPENDIX G. SURVEY 123 FORM USED FOR MODEL VALIDATION

Screenshot examples of Survey123 forms used on field staff's iPhones to collect model validation site data. A table of collected metrics used to create the Survey123 forms follows.





Model Validation Assessment Metrics
Site Description
Site ID -> *open entry*
Date -> *open entry*
Observers -> *open entry*
Site Location -> *open entry*
Location Notes -> *open entry*
Site Description -> *open entry*
Site Photo 1 -> *image file*
Site Photo 2 -> *image file*
Site Photo 3 -> *image file*
Site Photo 4 -> *image file*
Plant Community Type -> *select one*
Mesic Aspen
Dry Aspen
Wet Meadow
Mixed Mountain Shrubland
Sagebrush
Montane Grassland
Willow Carr
Riparian
Alpine Meadow
Pinyon-Juniper
Spruce-Fir
Mixed Conifer
Irrigated Agriculture
Lodgepole Pine
Wetland Other
Tree/Shrub Characterization
Tree/Shrub Cover -> *select one*: 0-10%; 10-25%; 25-60%; 60-100%
What % of AVAILABLE Trees/Shrubs are Palatable (Nonpalatable: Conifers, Symphoricarpos, Chyrsothamnus, Diasphora, Ericamerica) -> *select one*:
Greater than half (>50%)
Nearly half (25-50%)
Less than 25%
Browsing Pressure on Trees/Shrubs -> *select one*:
Little or no hedging: 0-40% twigs browsed
Moderate hedging: 41-60% twigs browsed
Severe hedging: >60% of twigs browsed
Browse Availability of Palatable Shrubs and Trees -> *select one*: all available; moderately available; unavailable
Forb Characterization
Number of Forb Species Present -> *open entry*

Model Validation Assessment Metrics
Forb Cover -> select one: 0-10%; 10-25%; 25-60%; 60-100%
Graminoid Characterization
Number of Graminoid Species Present -> *open entry*
Forb Cover -> *select one*: 0-10%; 10-25%; 25-60%; 60-100%
Non-native Bromus >20% Cover? -> *select one*: yes; no
Cover, Water Disturbance
Distance to thermal hiding cover (>2m height and at least 30x30 sq meters) -> *select one*: <50m; 50-100m; >100m
Water resources within 250m -> *select one*: yes; no
Anthropogenic features within 250m -> *select all that apply*: primary road; secondary road; house/building; other
Notes on Anthropogenic Disturbance -> *open entry*
Notes on Observed Grazing Impacts -> *open entry*
Notes on Wild Ungulate Signs -> *open entry*

APPENDIX H. TECHNICAL METHODS FOR HABITAT QUALITY – ELK & MULE DEER

Food Resources

Irrigated Agriculture

We used the forage quality models for elk and mule deer described in Appendix C of this report as the base data for the food resources component of habitat quality. Those models reflect relative forage quality as expressed through the richness and abundance of palatable plants in naturally-occurring ecosystems across winter and growing seasons (spring, summer, fall). In recognition of the additional forage opportunities that irrigated agricultural fields contribute to food resources, we used the Colorado Water Conservation Board/Division of Water Resources *Irrigated Lands* database (2015, https://www.colorado.gov/pacific/cdss/division-5-colorado) to develop a layer for irrigated agricultural fields, which was overlaid onto the forage quality models. These data were modified using source descriptions from the database, in combination with aerial imagery, to restrict the dataset to agricultural lands, and to remove other irrigated lands (e.g., lawns, golf courses). We assigned a quality score of "Moderate" to all irrigated agricultural fields. The moderate score reflects the trade-offs between abundant, nutritious forage during limited portions of the year, and the ecological and human conflict costs of prolonged ungulate use of agricultural fields (addressed in Forage Quality section of this report).

Topographic Wetness Index

We created the topographic wetness index as a relative measure of how moisture collects on the landscape. During our field investigations, we observed that sites with high levels of species diversity and abundance of palatable plants, were often associated with nearby wetlands, wet meadows, and other mesic habitat types. To reflect this, we used the U.S. Geological Survey 10m elevation model to apply 'wetter' and 'drier' modifiers to the forage quality model. The data values of the Topographic Wetness Index are close to evenly distributed, so we defined 'wetter' as anything greater than 1 standard deviation above the mean, and 'drier' as lower than 1 standard deviation below the mean. The topographic wetness index is only one measure of wetness. It was added to complete treatment of wetness in the overall analysis. Other components of wetness include landform and exposure (incorporated into the forage quality classification) and springs and other wetlands (incorporated into the Conservation Importance layer described later in this report).

There are seasonal differences in the influence of moisture on elk and mule deer habitat. Snow in particular helps dictate the seasonal movements and distribution of ungulates in temperate systems (Montieth et al. 2011, Geremia et al. 2014, Montieth et al. 2018). In winter, drier areas (i.e., less snow) offer better access to forage and reduce the energetic costs associated with moving through deep snow (Parker et al. 1984). During the growing season, wetter areas offer more forage and better nutrition.

Therefore, we used the Topographic Wetness Index (Figure H-1) to modify the forage quality models as follows:

- 'Wetter' areas increased the forage quality scores in the growing season model by 1 (i.e., Low -> Moderate, Moderate -> High, High -> Very High).
- 'Drier' areas increased the winter forage quality score by 1.

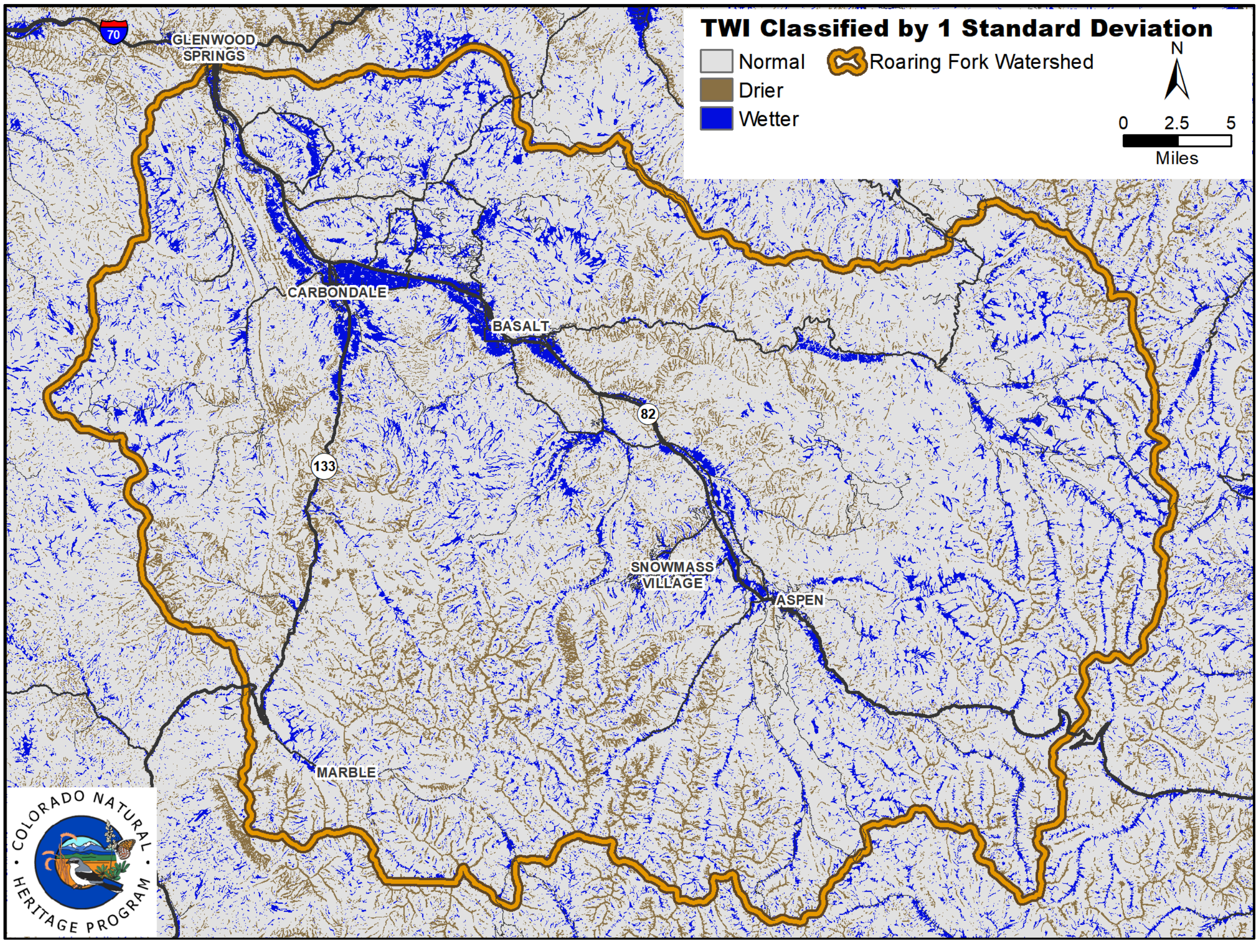


Figure H-1. Topographic wetness index for the Roaring Fork Watershed.

Shelter

Shelter for large ungulates in most natural ecosystems is provided primarily by vegetation (usually trees and shrubs). There are no empirical data available for the Watershed addressing the quantitative cover requirements for elk and mule deer, including how they seasonally optimize the tradeoff between high quality forage resources and cover. Therefore, generalizations based on the literature and Science Team input were used to develop seasonal scoring curves for distance to cover and percent canopy cover for trees and shrubs, i.e., the influence of "shelter" on habitat quality. Dense tree cover and moderately dense shrub cover offer escape cover and thermoregulatory cover, while still allowing animals to move through the forest or shrubland. To assess this habitat factor, we used two components of the LANDFIRE Remap 2016 vegetation layer (30m resolution, July 2020): *Existing Vegetation Cover* and *Existing Vegetation Height ≥ 3m* to map tree canopy and shrub canopy. Because of the presence of some large (>40,000 hectare), recent wildfires (e.g., Lake Christine Fire) and beetle kill areas, we used layers from the National Interagency Fire Center and U.S. Forest Service aerial surveys to subtract areas of recent (within the last 5 years) reductions in tree and shrub cover from wildfires and beetle kill from the LANDFIRE vegetation map (Figure H-2). We subtracted both beetle kill and fires from the tree canopy. Only fires were subtracted from the shrub canopy. Beetle kill data provided a "dead trees per acre" attribute that we were able to convert to percent cover. Because comparable attributes were not available in the wildfire data, we gave fires a blanket 50% reduction in cover. Though this reduction is not uniformly accurate, burned areas tend to be patchy, and we determined that 50% was a reasonable approximation. We then used the cover layers to identify areas of high forage quality that are adjacent to good shelter and weighted those complexes (food + adjacent shelter) higher overall in scoring habitat quality.

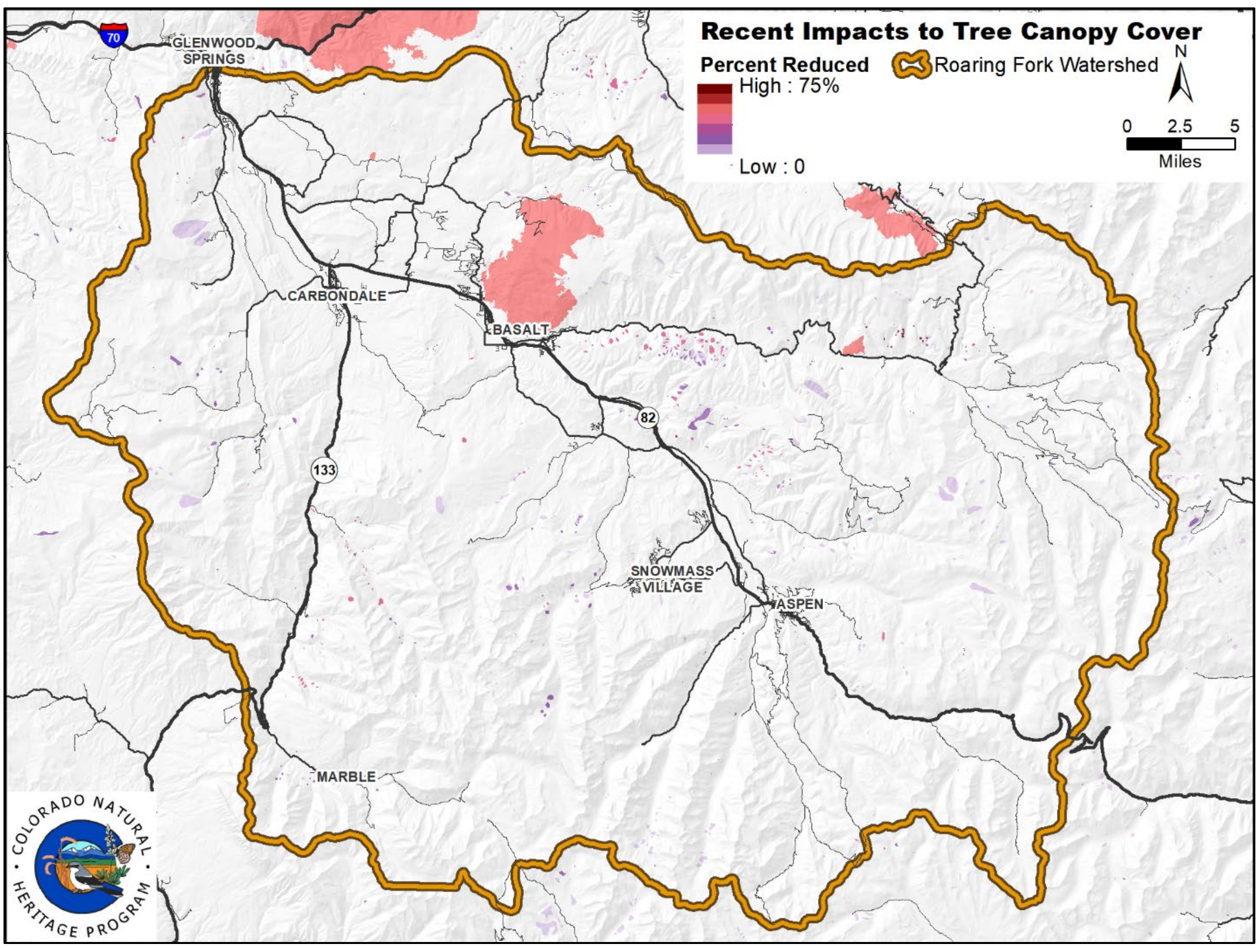


Figure H-2. Recent reductions in tree and shrub canopy from beetle kill and wildfire.

Winter

For winter season, "adjacent" was considered twice the distance used for summer due to lower food availability. In winter, the *further* away from *denser* cover, the greater the decrease in habitat quality score. Within 515 m, the habitat quality score is equal to the modified forage quality score (515m number is used for consistency with growing season). From > 515m to 2 km, habitat quality equals linearly decreasing forage quality. Beyond 2km, habitat quality score becomes Low (Figures H-3 and H-4). The same density response curves were used for winter as for growing season:

- Scoring Curve for **Trees** >= 3m in Height
  - High Quality: Tree Cover 40-100%
  - Moderate Quality: Tree Cover 20-39%
  - Low Quality: Tree Cover 0-19%

- Scoring Curve for **Shrubs** >= 3m in Height
  - High Quality: Shrub Cover 40-65%
  - Moderate Quality: Shrub Cover: 20-39% and 66-84%
  - Low Quality: Shrub Cover 0-19% and 85-100%

Finally, for both seasons, areas too small to act as cover (< 90m x 90m, Rowland et al. 2018) were removed. Results were reclassified into the Low, Moderate, and High quality.

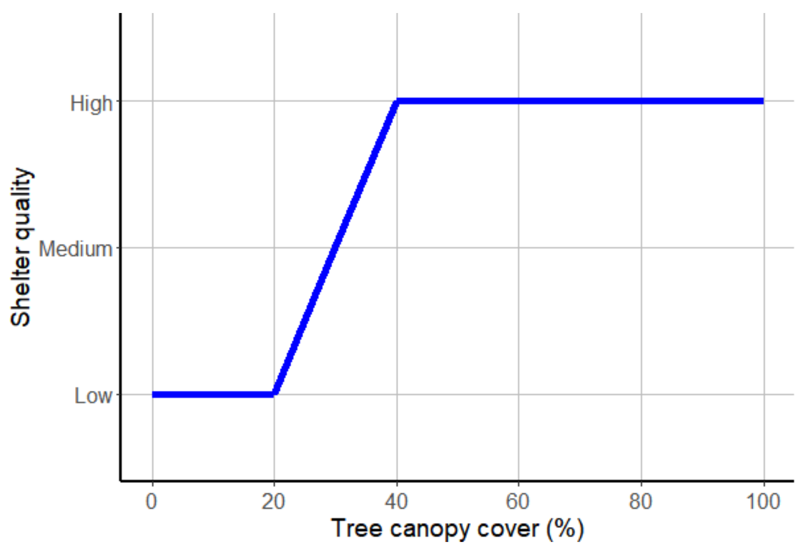


Figure H-3. Scoring curve for tree canopy cover.

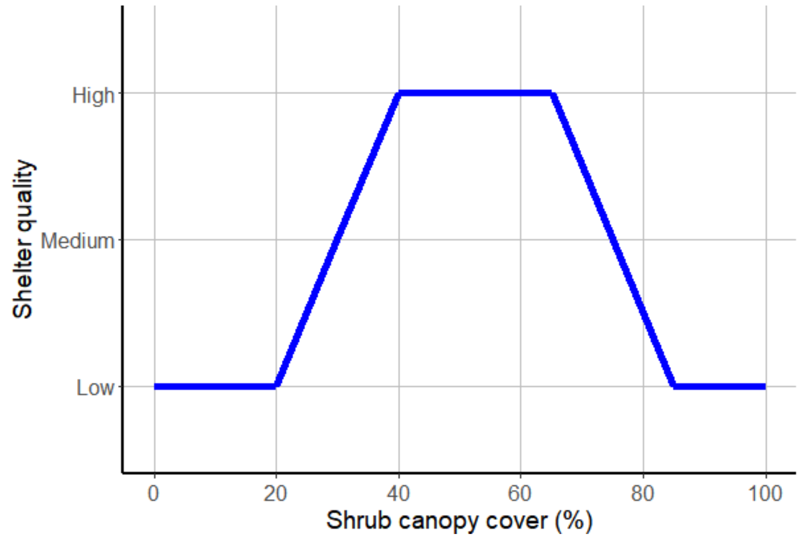


Figure H-4. Scoring curve for shrub canopy cover.

Growing Season

For the growing season, we defined "adjacent" as cover (tree and/or shrub) within 515m (Rowland et al. 2018, Figure H-5), with terrain taken into account (i.e., 'as the ungulate walks' as opposed to 'as the crow flies'). The *nearer* high quality forage areas are to *optimal* canopy cover as defined by the scoring curves (Figures H-3 and H-4), the greater the habitat quality score. We made one exception to this rule: cover weighting was not applied to alpine habitat for elk because above treeline, rough topography is far more likely to offer hiding cover than any low-growing alpine shrubs. Elk are known to heavily use alpine areas that are far from cover (e.g., Zeigenfuss 2006), and the Roaring Fork Science Team concurred that proximity to tree/shrub cover was not an important criteria of habitat quality in the alpine.

Relative quality was scored separately for canopy cover of trees and shrubs using a scoring curve adapted from the Colorado Mule Deer Habitat Quantification Tool. The general cutoffs for the habitat quality classes are as follows:

- Scoring Curve for **Trees** >= 3m in Height
    - High Quality: Tree Canopy Cover 40-100%
    - Moderate Quality: Tree Canopy Cover 20-39%
    - Low Quality: Tree Canopy Cover 0-19%
- Scoring Curve for **Shrubs** >= 3m in Height
    - High Quality: Shrub Cover 40-65%
    - Moderate Quality: Shrub Cover: 20-39% and 66-84%
    - Low Quality: Shrub Cover 0-19% and 85-100%

Linear distance decay was based on Rowland et al. (2018), who reported a range of effect decay slopes (min: -1.2554, max: -0.3855). We used -0.388 with an intercept of 100 * Modifier Weight: y = -0.388x + 200. This makes the actual maximum distance to have any effect 515m.

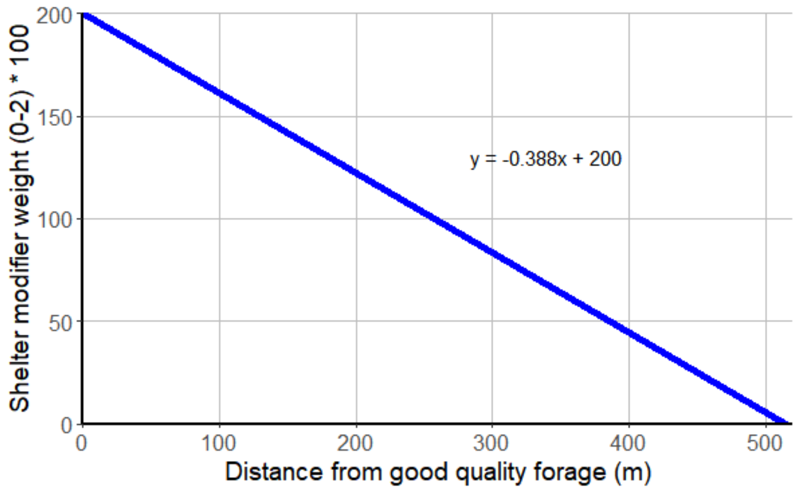


Figure H-5. Effect of proximity between shelter and high quality forage as used for growing season.

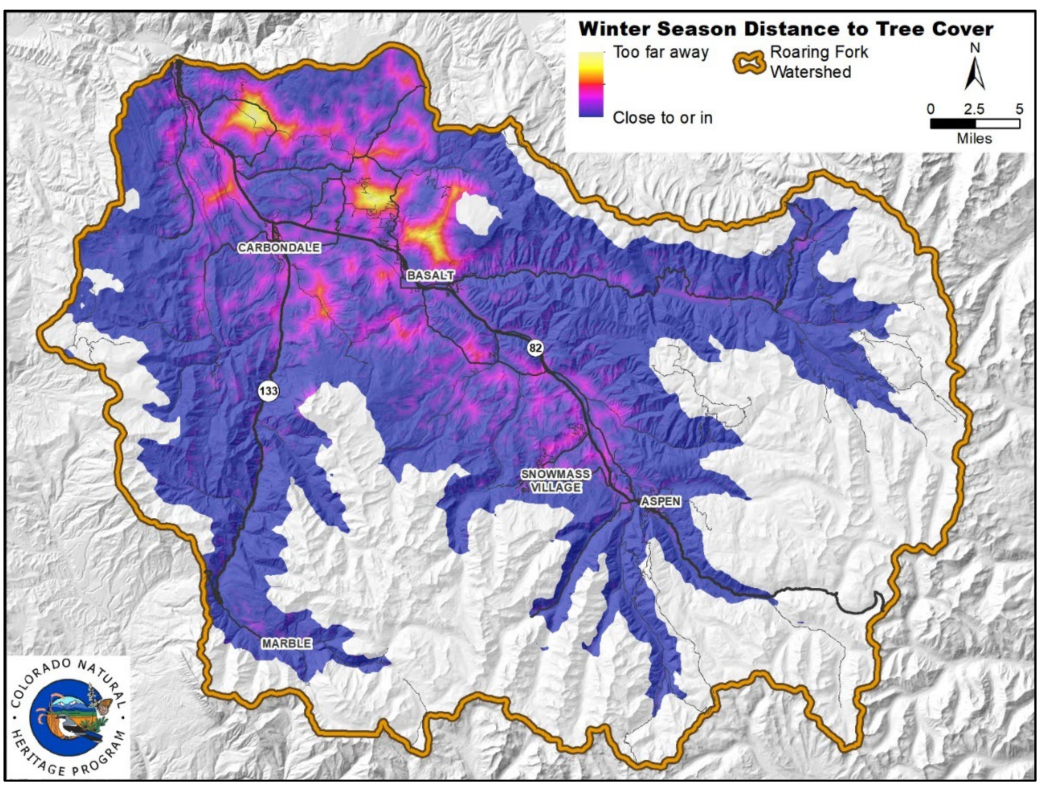


Figure H-6. Distance to tree cover in winter.

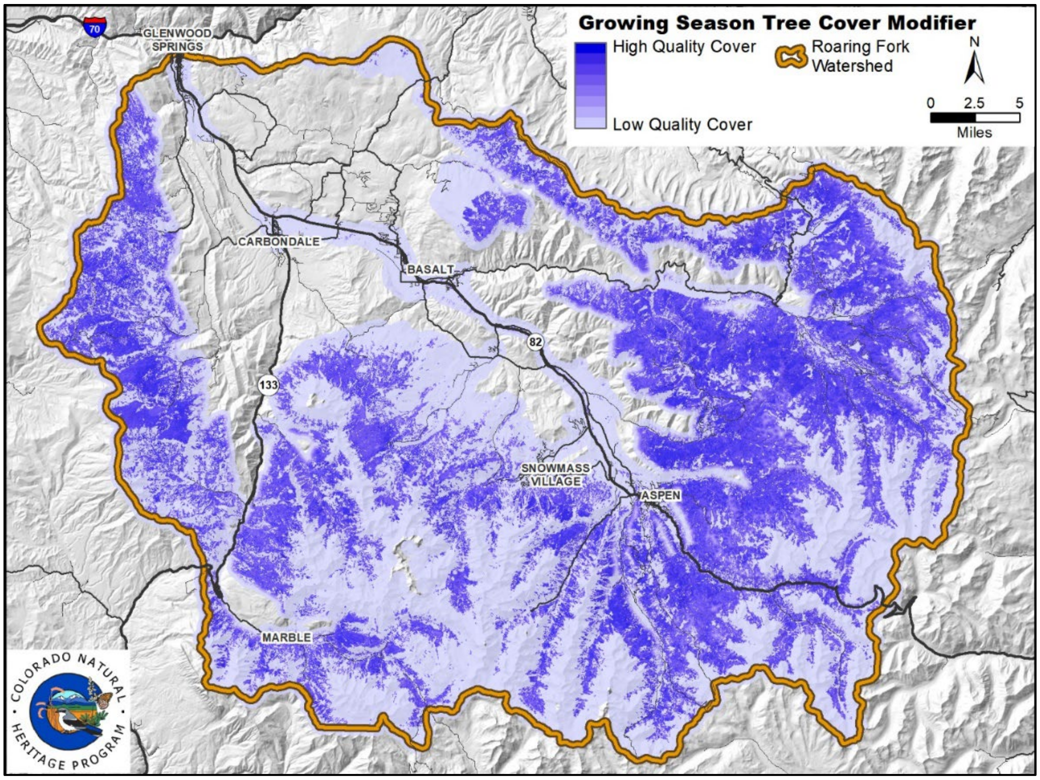


Figure H-7. Tree cover modifier in growing season range.

Landscape Disturbance & Connectivity

The Landscape Disturbance Index (LDI; see Appendix J) was used as a modifier to the Food + Shelter Models for growing season and winter, as follows:

- Areas of Moderate anthropogenic impact (LDI between 250 and 500); the habitat quality score was reduced by 1 (i.e., High score reduced to Moderate, Moderate score reduced to Low). This was done for the elk/deer combined winter model and for the mule deer growing season model.
- For the elk growing season model, Moderate anthropogenic impact was defined as the LDI range 240 – 500 to better reflect the stronger avoidance of roads by elk, whereas in winter, there is less choice of available habitat, so elk and deer were presumed to behave similarly.
- Areas of High anthropogenic impact (LDI ≥500) became Low Habitat Quality. Urban areas are mapped as not habitat.

We used the deer and elk permeability model, the habitat quality models, and CPW's Species Activity Mapping to identify corridors between areas of high quality habitat. We concentrated on movement between the transition area between winter and summer ranges (within the watershed only) for both elk and mule deer (see Appendix I for details). Anthropogenically-caused connectivity constrictions (i.e., "pinch points") within the corridors were identified using the Landscape Disturbance Index and manually verifying the pinch points using aerial imagery. Finally, we added CPW SAM Migration Corridors that were contained entirely within the Watershed for both elk and mule deer.

APPENDIX I. TECHNICAL METHODS FOR LANDSCAPE PERMEABILITY AND CONNECTIVITY

Landscape Permeability

We modeled landscape permeability using land cover, roads and trails, fences, topography, and oil and gas layers for elk, mule deer, and bighorn sheep. Permeability in this case refers strictly to ease of movement of individual animals through the landscape. Land cover and land use were based on USGS-GAP (2016) and CODWR (2015); roads, trails, and fences were from county government provided roads and CDOT (2018); and oil and gas from Eisinger (2021). Table I-1 provides the permeability scores assigned to these data. With the exception of riparian vegetation, which were scored separately for deer and elk, the same scores were used for the 3 ungulate species. Differences in species movement preferences were addressed in the topographic components of slope and measures of surface roughness calculated from a 10m elevation dataset (USGS 2013).

The influence of topography was addressed by modeling simplified responses of the 3 ungulate species to variations in terrain relief (surface relief ratio) and steepness (surface:area ratio). Due to similarity in habit, deer and elk were given the same responses. These responses are based on common knowledge of the species' habits and not empirical data, which is unavailable. Table I-2 describes these general responses and Figures I-1 and I-2 show the curves created to represent the responses.

Table I-1. Permeability scores assigned to land cover / land use types and other structures.

Data Type	Category	Score	Rationale
Land Cover	Forests & Woodlands	10	Trees easier to move through, offer more cover
	Most shrubland types	8	A little harder to move through, offer less cover
	Some shrubland types (saltbush, desert scrub) †	6	less cover, harsher climate conditions
	Grasslands, irrigated agricultural fields	7	Lack of cover
	Barren lands, disturbed / converted / developed areas	3	No cover, human disturbance
	Riparian		For elk and deer only: Rivers buffered 100m; streams buffered 30m; added extra 1 point for land cover types scored 7-9 to reflect importance of riparian vegetation as movement corridors
Roads and Trails	Interstates*	1	
	Highways (major)*	2	
	Highways (smaller)*	3	
	Arterials (major)	4	
	Arterials (minor)	5	
	Collectors, local city roads	6	
	Local rural, 4wd, motorized trails	7	
	Bike trails, dogs allowed on trail	8	
	Unknown trail	9	
	Pedestrian only trail	10	
CDOT Fences	Bridge safety, chain link w/ barbed wire; game fence/ wildlife fence	1	
	Chain link	2	
	5-strand barbed wire	5	
	Non-barbed wire, "other"	6	
	Snow fence, wood w/ rock supports	8	
	Wood	9	
Oil & Gas	Wells, pits, tank batteries	3	Same score applied to "barren" land cover type; buffered point locations by 100m (estimate of disturbance based on aerial imagery)

* Modified by annual average daily traffic when available.

† The analysis was done at a larger scale than the Watershed and so includes some vegetation types that may not occur within the Watershed itself.

Table I-2. Simplified species responses to varying terrain.

Species	Surface Relief Ratio (values)	Surface:Area Ratio (values)
Elk and Deer	Avoid strongly mixed relief (~0.5) Preference for lowland (0) Somewhat less preference for upland (1.0)	Avoid very steep (< 0.5) Prefer flat (1.0)
Bighorn Sheep	Avoid lowlands (0) Prefer uplands (1.0) In between for mixed relief (~0.5)	Prefer moderate steepness (~0.5 - 0.9) Avoid impossibly steep (< 0.25) Less preference for flat (1.0) *

* This is not because bighorn sheep actually avoid flat ground, but is used as a proxy for their preference for rough terrain to escape predators.

Surface relief ratio (SRR; Pike 1971) gives the relative proportion of upland to lowland within a specified area on the landscape. A value of 0 = all lowland, 0.5 = max roughness, and 1.0 = all upland. This metric is scale dependent and values, particularly those between 0.4-0.6, can represent different terrain types, so the scale independent surface:area ratio was used as a complimentary metric. For this analysis, a 300m radius circle was used to provide a reasonable scale for surface relief to affect large mammal movement.

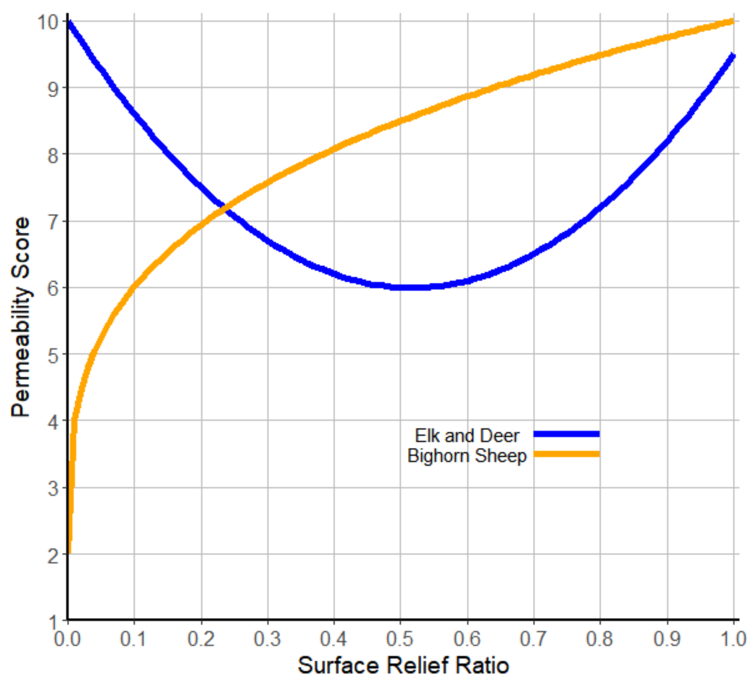


Figure I-1. Surface relief ratio response curves based on Table I-2 species responses.

The surface:area ratio is a planimetric-to-surface area ratio that describes the level of steepness in a single raster pixel. Values range from near 0 (extremely steep) to 1 (flat). For reference; a value of 0.4 is a 66° slope, and 0.9 is a 25° slope.

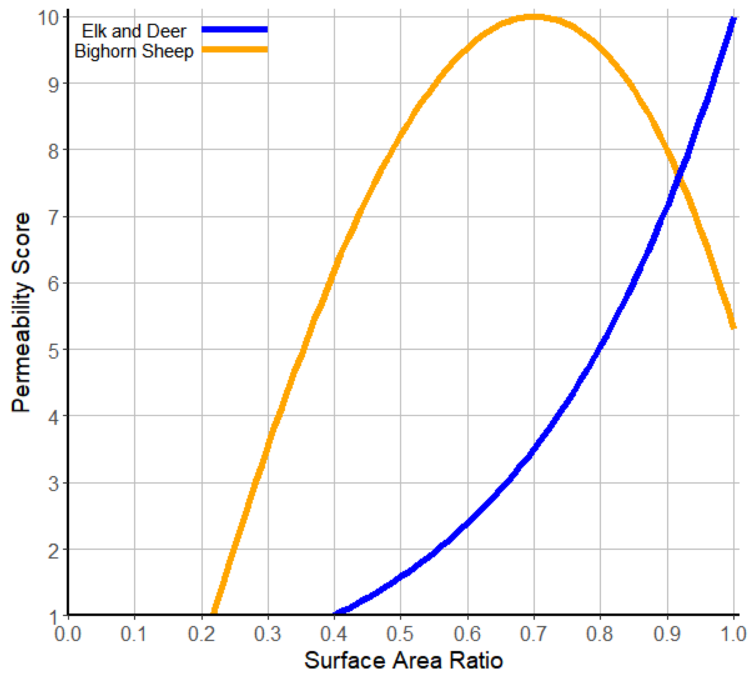


Figure I-2. Surface:area ratio response curves based on Table I-2 species responses.

All permeability scores were combined into Permeability Models for deer and elk together and bighorn separately such that if any permeability value <= 5, the minimum of all inputs was taken, otherwise the arithmetic mean of all inputs was used. The Permeability Models were originally created in 2019. When deer and elk corridors were refined in 2021, the deer and elk model was modified to account for dense shrub canopies that are difficult for ungulates to move through. We defined "dense" as >70% shrub cover (Rowland et al. 2018).

Connectivity

We used the deer and elk permeability model (Figure I-3), the habitat quality models, and CPW's Species Activity Mapping to identify corridors between areas of high quality habitat (Figure I-4). We concentrated on movement between the transition area between winter and summer ranges (within the watershed only) for both elk and mule deer. Anthropogenically-caused connectivity constrictions (i.e., "pinch points") within the corridors were identified using the Landscape Disturbance Index (Appendix J) and manually verifying the pinch points using aerial imagery. Finally, we added those CPW SAM Migration Corridors that were contained entirely within the Watershed for both elk and mule deer.

For bighorn sheep, a separate landscape permeability model was used only to identify escape habitat (Figure I-5) as a part of its habitat quality model, *not* for movement corridors. One of the key threats facing bighorn sheep herds in Colorado is disease transmission between livestock (especially domestic sheep, but also cattle and goats) and bighorn sheep. Under these conditions, connectivity among herds and habitats is *not* desirable (George et al. 2009), and was therefore not used as a component of habitat quality.

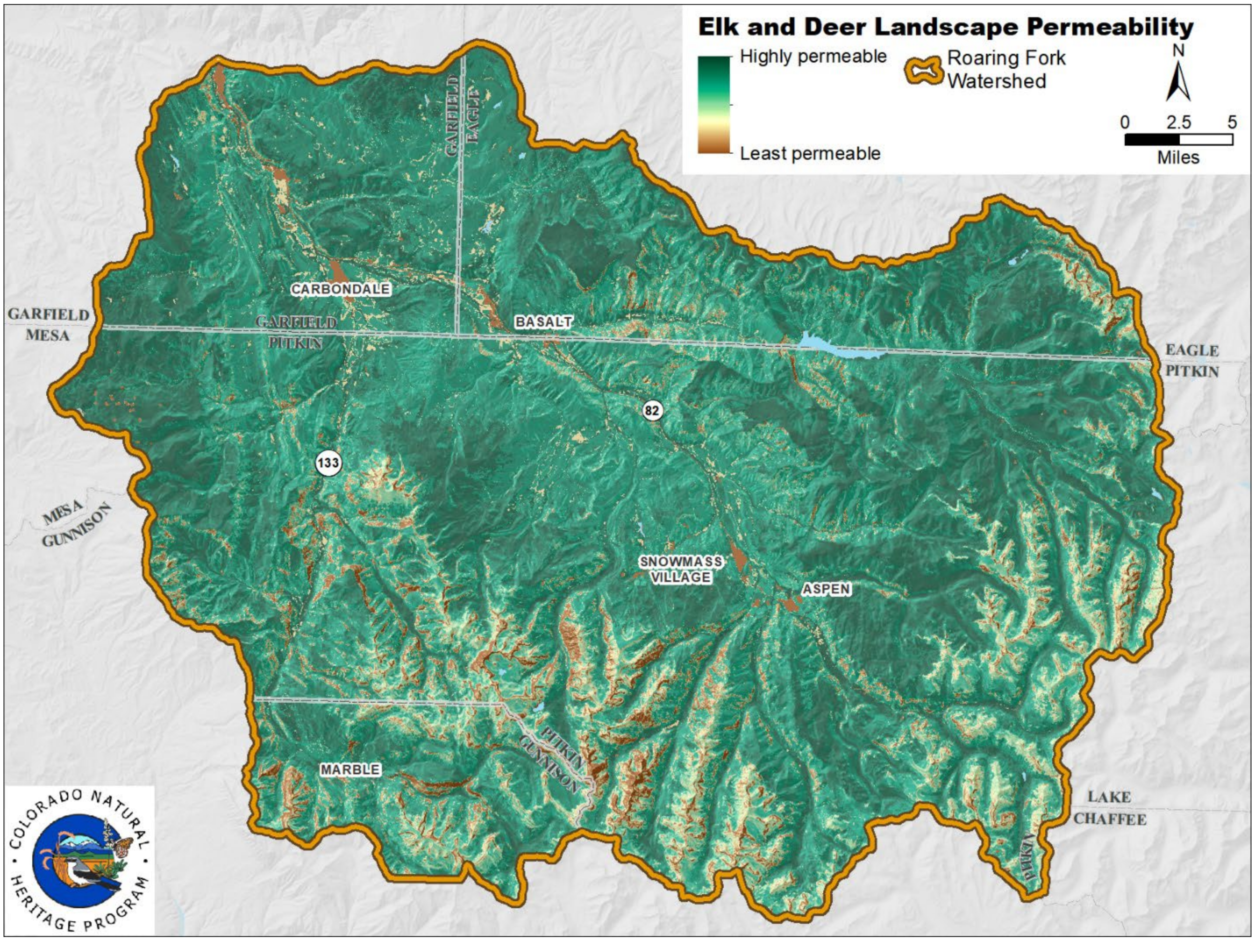


Figure I-3. Landscape permeability for elk and mule deer in the Roaring Fork Watershed.

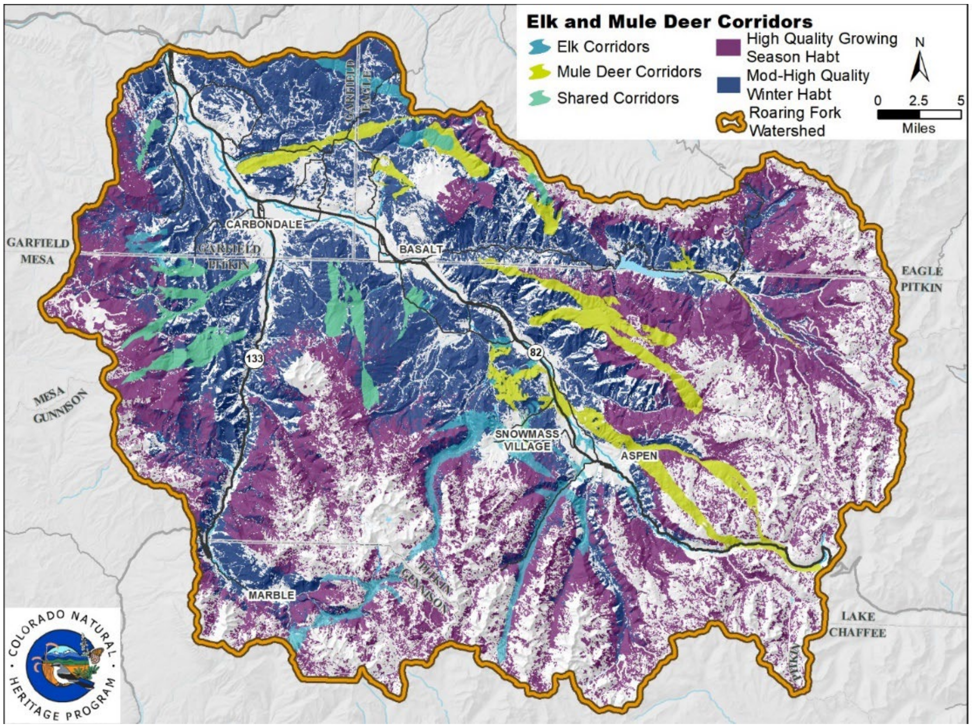


Figure I-4. Modeled movement corridors for elk and mule deer in the Roaring Fork Watershed.

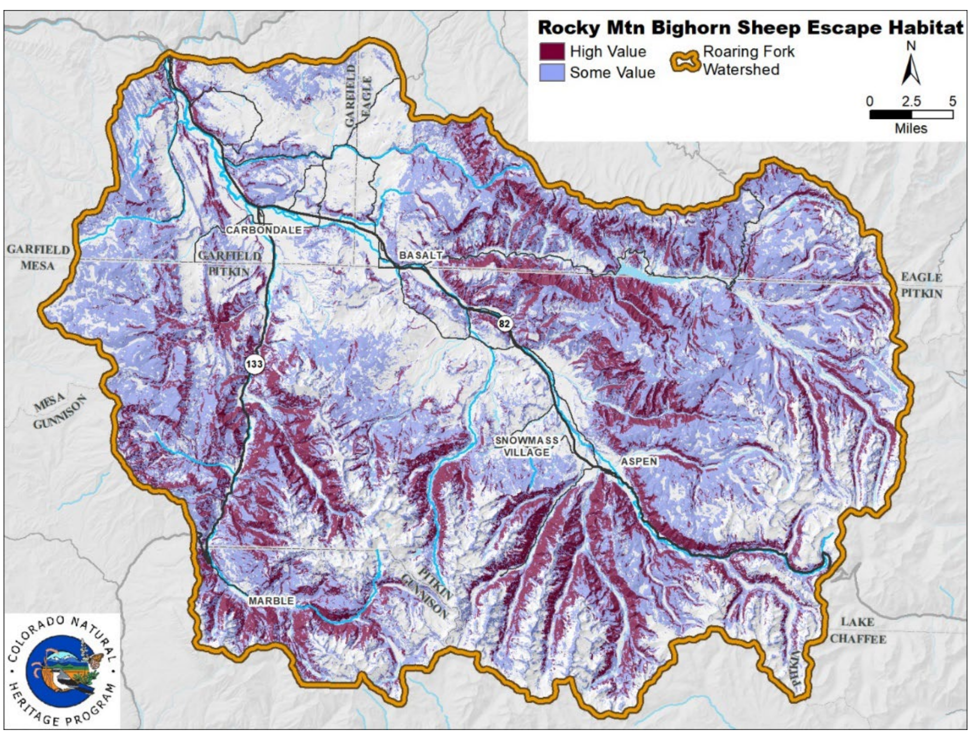


Figure I-5. Modeled escape terrain for bighorn sheep in the Roaring Fork Watershed.

References

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APPENDIX J. TECHNICAL METHODS FOR LANDSCAPE DISTURBANCE INDEX

Evidence for effects that reach beyond the boundaries of the footprint of an anthropogenic disturbance has been documented in a variety of studies. Road-zone effects have been especially well documented, showing effects for various taxa of anywhere from 100 to 1000 meters (Boarman and Sazaki 2006, Palomino and Carrascal 2007, Wilbert et al. 2008, Eigenbrod et al. 2009, Parris and Schneider 2008, and others). Other disturbance types are not as well studied, but there is evidence for effect-zones for both urban and exurban development (Odell and Knight 2001, Hansen et al. 2005, McDonald et al. 2009), energy development (BLM 1999, Wilbert et al. 2008, Nasen 2009, Lovich and Ennen 2011, Naugle 2011), recreational trails (Hennings 2017, Gaines et al. 2003), unleashed dogs (Stankowich 2008, Silva-Rodriguez and Sieving 2012), and agriculture (Davis et al. 1993, de Jong et al. 2008). Due to the nature of the research, effect-zones are usually specified as applying to a particular taxa or guild. In addition, some species respond positively to anthropogenic disturbance. While it would be ideal to construct a disturbance effect model for every species or group of species within an area of interest, for practicality, we chose to generate a generalized LDI.

Under the generally accepted premise that the magnitude of anthropogenic effects decreases with distance from the source of disturbance (Theobald et al. 1997), Tuffly and Comer (2005) used a distance-decay function of the form Impact = (1/distance)*Weight of impact, which reaches values close to zero within a few hundred meters, but without truncation leaves a small residual amount of disturbance as a background throughout the entire model. Later work recognized the need for either post-processing to relativize background values (Vance 2009), or truncation of a decay function at a set distance during model construction (Decker and Fink 2008, Vance 2009, Rondeau et al. 2011). We chose to use a distance based decay function to simulate an effect which is quite strong adjacent to the disturbance footprint but declines fairly quickly to a base level near zero, i.e., a sigmoid curve.

The distance-decay function represents a mathematical curve describing degree of influence over distance. A variety of curves can be used for distance decay models. The choice of curve for the distance decay function is determined by how the disturbance is believed to behave in the real world, i.e., does the effect drop sharply near the source but then fade gradually (log function), or perhaps maintain a noticeable effect for some distance away from the source before decreasing (e.g., sigmoid-curve, witch of Agnesi), or is the rate of decrease constant (i.e., linear)? Many potential curves are asymptotic at one or both ends, in which case the values can be artificially truncated at a distance thought to reflect the actual radius of the disturbance effect. Naturally the technique does not account for impacts which only have an effect in a limited direction from the impact (e.g., only downstream or downwind).

Curve type and impact values were developed and refined in discussions with partners engaged in conservation management. These discussions considered the relative impacts and apparent distance over which those impacts were believed to add to the disturbance of an otherwise intact landscape. Although there are few studies that quantify the effect over distance of various anthropogenic effects, wherever possible, we used studies from the literature to inform our choices of impact and distance of effect. Thus, for instance, an estimate of the average area of impact resulting from drilling a single oil or gas well was translated into an area around a point within which impact was expected to be significant. So, although our choice of curve type and impact values are generalized to nice round numbers, they are loosely based on observations documented in studies of the distance effects and impact areas of anthropogenic disturbances.

We chose to limit the distance beyond which our modeled disturbance would have an effect, even though some types of disturbance such as atmospheric deposition of particulate matter have effects documented at continental scales (Grantz et al. 2003). The curves used in our model are of the sigmoid function shown below:

$$y = \frac{1}{1+\exp\left(b\left(\frac{x}{c}-a\right)\right)} \times w$$

where:

a - shifts curve to right or left

b - determines spread of curve (slope of the rapidly decreasing part of curve)

c - inflection point (or scalar to adjust total distance of interest)

x - distance in meters from impact

w - weight of impact (maximum value at 0 distance)

By adjusting the shift and spread of the curve (a and b), it can be tailored to the known or suspected behavior of specific impacts. Different values of a and b were used to derive four decay curves describing gradual, moderate, moderately abrupt, and abrupt distance decay behavior (Table J-1). The inflection point of the curve marks the distance where the effect of the impact is reduced by half. These curves are asymptotic at both ends, therefore the results of the equation must be manually adjusted to equal the maximum weight at zero distance and minimum weight at a distance at which the weight becomes essentially zero ("cutoff distance").

We created a watershed-specific index following methods described in Decker et al. (2017), except that in the Roaring Fork Watershed irrigated agriculture was not treated as a potentially degrading impact. Land uses incorporated into the LDI included urban and exurban development, roads and trails, energy development infrastructure (oil and gas wells), and surface mining.

Each individual layer has its own relevant weight and decay function type (Tables J-1 and J-2, Figure J-1). These layers are not mutually exclusive in the impacts they represent, and are in fact chosen to complement one another so as to make up for incomplete and inaccurate source data. The individual impact layers were then additively combined to produce an overall disturbance layer, representing relative levels of impact (Figure J2). For simplicity, the categorizations shown in Table J-3 are used, instead of the raw index value.

Table J-1. Land use layers used to develop the Landscape Disturbance Index.

Impact Type	Weight	Decay Function	Original Data Source*
Development – High/Medium	500	Gradual	Landfire 1.3 & NLCD 2014
Development – Low	300	Gradual	Landfire 1.3 & NLCD 2014
Roads – Major	500	Moderate	TIGER/Line 2019
Roads – Local	300	Abrupt	TIGER/Line 2019
Roads – 4WD & Motorized trails	250	Abrupt	TIGER/Line 2019 & COTREX Trails 2019
Trails – Unleashed dogs	200	Abrupt	COTREX Trails 2019
Trails – Other	100	Very abrupt	COTREX Trails 2019
Oil & Gas Wells – Active	400	Moderate	COGCC 2021
Oil & Gas Wells – Inactive	200	Moderate/ abrupt	COGCC 2021
Surface Mines – Active	500	Moderate	CO-DRMS 2021
Surface Mines – Inactive	300	Moderate	CO-DRMS 2021

*Note that most sources were heavily edited and updated by CNHP using aerial imagery to improve accuracy.

Table J-2. Formula for each decay function.

Decay Function	Cut off Distance	Equation
Very-Abrupt	100 m	(1 / (1 + Exp(((Distance / 100) - 0.5) * 10))) * Weight
Abrupt	250 m	(1 / (1 + Exp(((Distance / 100) - 1) * 5))) * Weight
Moderate-Abrupt	600 m	(1 / (1 + Exp(((Distance / 100) - 2.5) * 2))) * Weight
Moderate	1250 m	(1 / (1 + Exp((Distance / 100) - 5))) * Weight
Gradual	2000 m	(1 / (1 + Exp(((Distance / 100) - 10) * 0.5))) * Weight

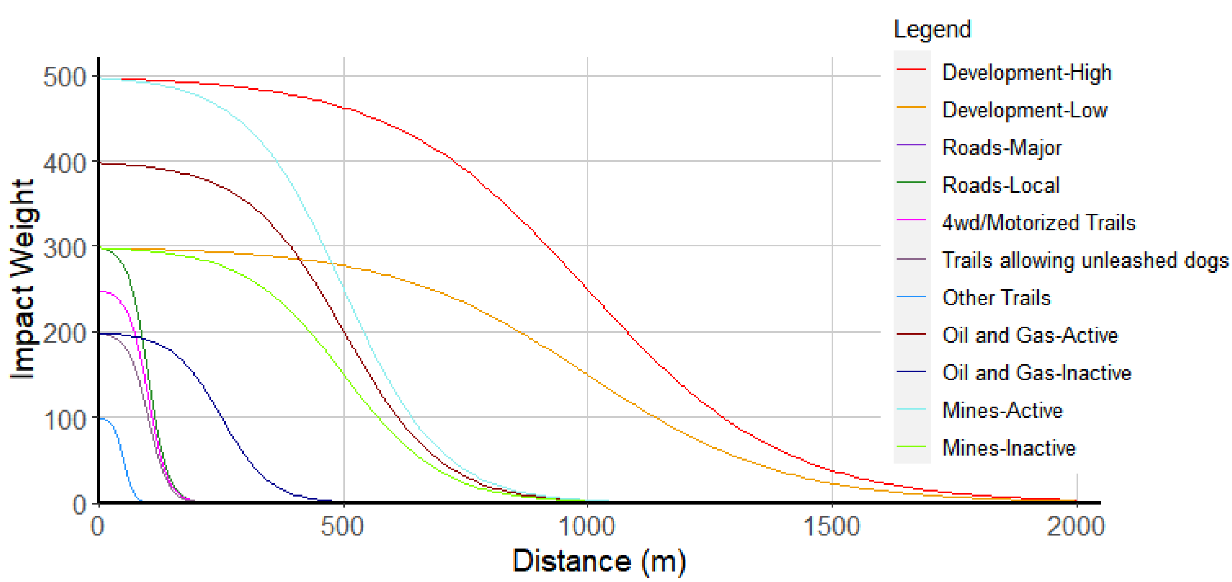

Figure J-1. Distance decay curves used in the Landscape Disturbance Index.

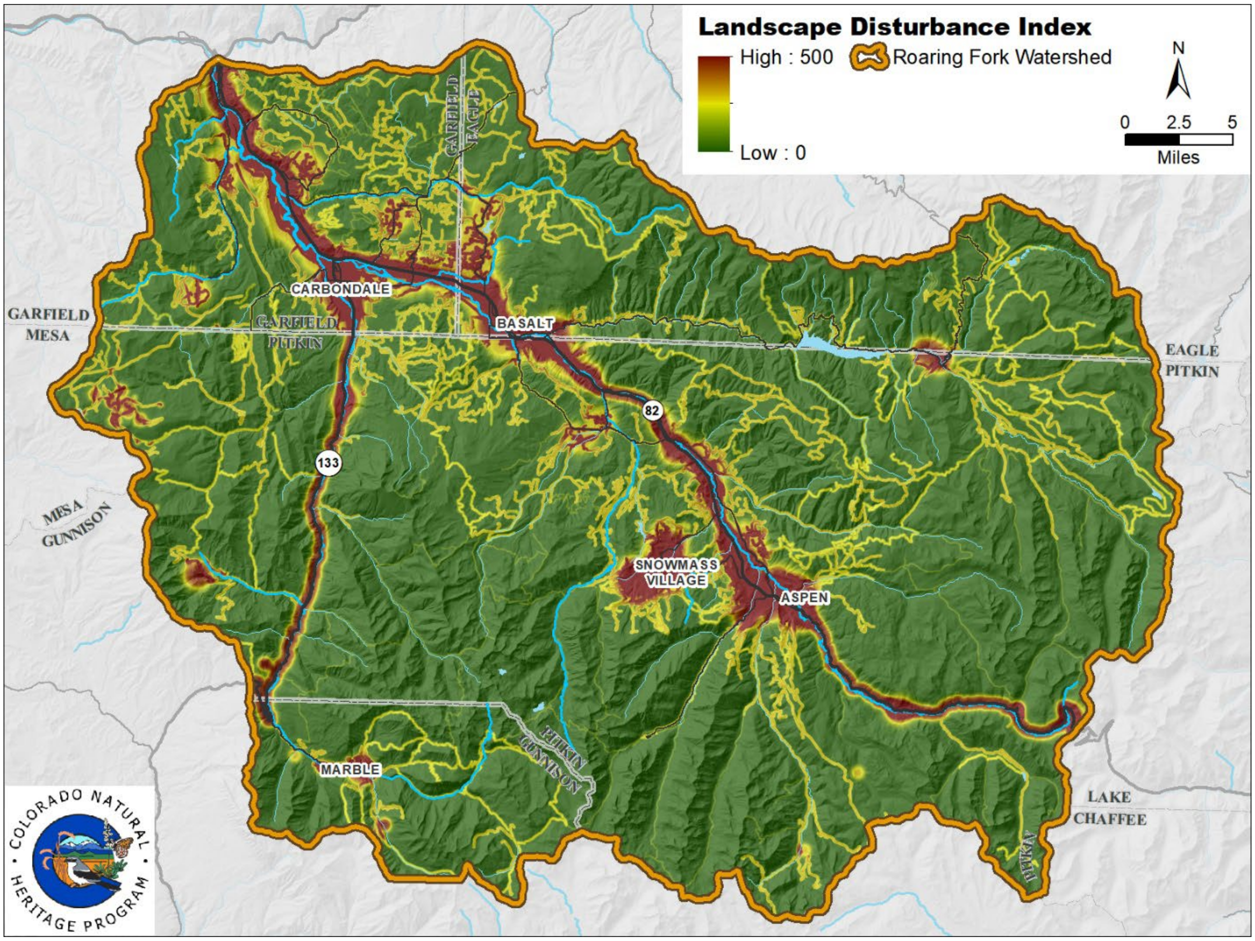

Figure J-2. Landscape Disturbance Index created for the Roaring Fork Watershed.

Table J-3. ***Landscape disturbance value ranges and corresponding categories of relative anthropogenic impact.***

Value Range	Level of Impact
0	None (or minimal)
>0 – 250	Low
>250 – <500	Moderate
>500	High

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APPENDIX K. TECHNICAL METHODS FOR HABITAT QUALITY – BIGHORN

In 2011, CPW biologists and GIS experts created a deductive habitat suitability model for bighorn sheep, with separate layers for summer, winter, and lambing habitat. This model was developed using animal movement data (telemetry consisting of ground very high frequency (VHF), aerial VHF, satellite, and GPS), slope, terrain ruggedness, canopy cover and vegetation (using LANDFIRE vegetation layer). It represents all the knowledge of bighorn sheep in Colorado, accumulated by CPW over many years. In consultation with CPW and the Science Team, we determined that this existing model was suitable for the purposes of our study, and that additional field effort was unlikely to improve it. Therefore, rather than collecting vegetation data in the field and developing our own model, we used CPW's model as the basis for mapping habitat quality for bighorn.

There is overlap among the summer, winter, and lambing models, and we wanted to use the same seasonal categories for bighorn as were used for elk and mule deer. So, we modified the CPW models such that summer and all lambing areas that did not overlap with winter were combined into a growing season model, and kept CPWs winter model as-is.

CPW's bighorn models reflect habitat and not habitat; there are no relative quality metrics to distinguish better habitat from less-good habitat. However, in 2008 Rocky Mountain Wild (RMW) created a habitat suitability model for bighorn that does contain quality metrics. The RMW model is a continuous, wall-to-wall surface, and as such, includes places that would never be bighorn habitat. We reclassified that bighorn habitat suitability model as Low = 0-60, Mod = > 60 - 75, High >75 (values in watershed range 19-100). Our classification is skewed because the RMW model values < 50 were mostly in areas that are not bighorn habitat.

We combined CPW's model and Rocky Mountain Wild's model to create single seasonal models (winter, growing season) that were not only spatially restricted—i.e., only include places that are actually habitat (CPW's model)—but also provided a means of identifying areas of higher quality habitat (Rocky Mountain Wild's model) (Figure K-1).

We made one final adjustment to the bighorn model to identify escape habitat. We used our bighorn permeability layer, reclassified as Low = 1-8, Moderate = >8 - 8.8, High > 8.8 (values in watershed range 1-9.8) to reflect relative value as escape habitat. This classification is based on how permeability was influenced by terrain steepness for bighorn, and is used in this instance as a proxy for steep escape terrain. The escape habitat was then added to the combined CPW/RMW model and became our seasonal bighorn sheep habitat quality models (Figures 25 and 26 in the main body of this report).

Note that, for bighorn, landscape permeability was used only to identify escape habitat, *not* movement corridors. One of the key threats facing bighorn sheep herds in Colorado is disease transmission between livestock (especially domestic sheep, but also cattle and goats) and bighorn sheep. Under these conditions, connectivity among herds and habitats is *not* desirable (George et al. 2009), and was therefore not used as a component of habitat quality.

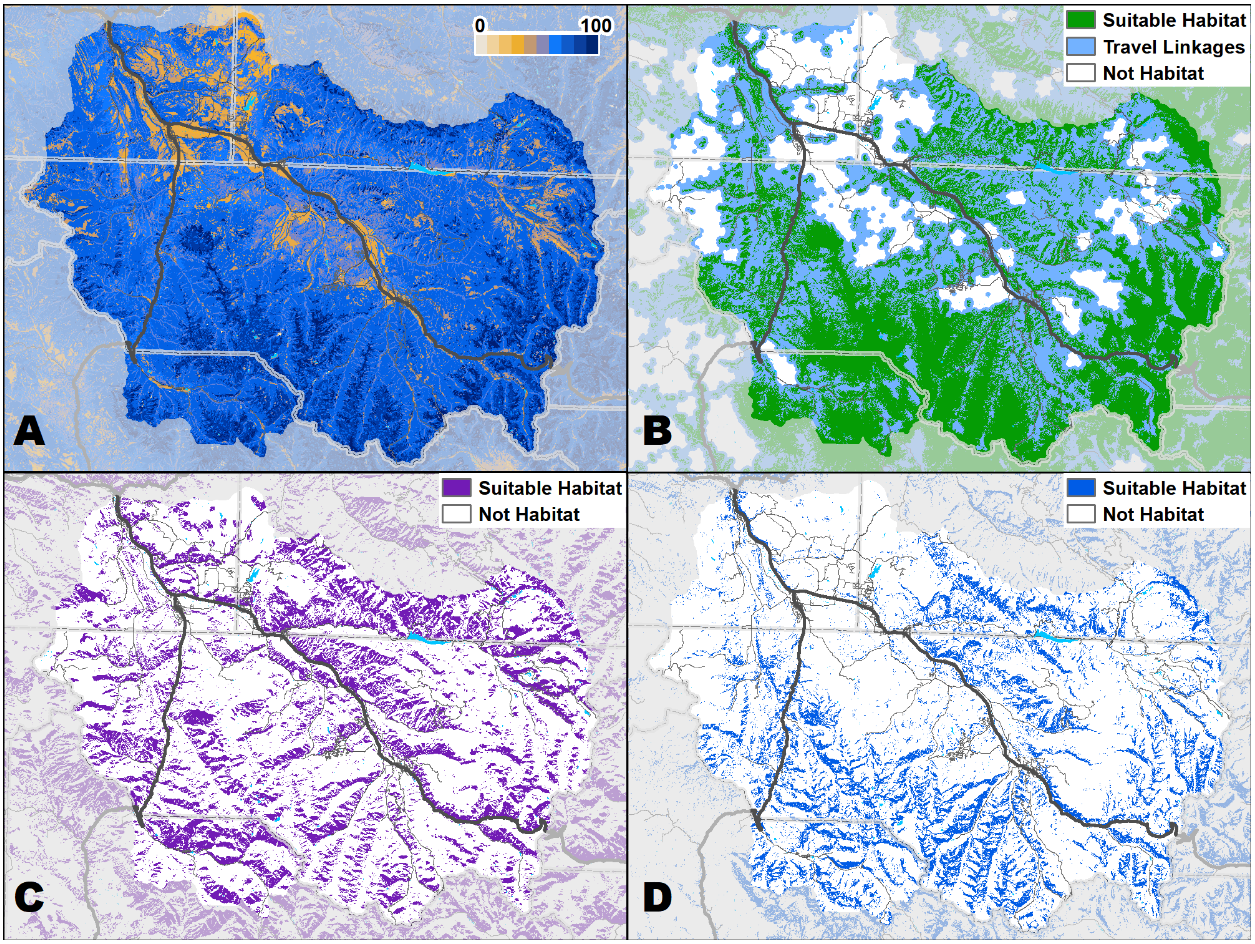

Figure K-1. Map images of source models used to create the habitat quality model for bighorn sheep. *A) Rocky Mountain Wild Bighorn Sheep Habitat Suitability Model; B) Colorado Parks and Wildlife Bighorn Sheep Summer Habitat (travel linkages component not used in our study); C) Colorado Parks and Wildlife Bighorn Sheep Winter Habitat; D) Colorado Parks and Wildlife Bighorn Sheep Lambing Habitat.*

APPENDIX L. TECHNICAL METHODS FOR CONSERVATION IMPORTANCE

To complement the habitat quality analyses for the focal species, we added a "Conservation Importance" component to the study that incorporates rare species, small-scale habitats such as wetlands, and other biodiversity values. We created two GIS layers to map Conservation Importance: "Key Areas" and "Biodiversity Importance." We defined Key Areas as relatively small and/or discrete areas that have a critical importance, or without which everything else has less value. Key Areas include, but are not limited to, areas of special importance for the focal ungulates. We used Biodiversity Importance to incorporate and prioritize rare or imperiled species and wetlands. Climate-change factors were included in both Key Areas and Biodiversity Importance.

For each data source incorporated into the Key Areas and the Biodiversity Importance layers, we scored inputs on a scale of 1-10. Scores were then summed, with higher scores representing higher priority for conservation and lower scores representing lower priority for conservation. Note that most individual inputs received a score of 1, and only inputs for extremely rare resources were given a score of 10. This was to highlight those areas where multiple inputs occur, as well as those areas with a single, very important input.

Key Areas

We used five data sources to create the Key Areas layer, as described below. Summing of scores resulted in a value range of 0-5. The final Key Areas layer is shown in Figure L-2.

Critical Areas for Elk, Mule Deer, and Bighorn

CPW's Species Activity Maps[9] for elk, mule deer, and bighorn, delineate places that have been consistently important for reproduction and winter survival over many years. These include:

- **Production** areas—that part of the overall range occupied by female elk from May 15 to June 15 for calving, or by pregnant female Bighorn May 1 to June 30 (dates for Rocky Mountain bighorn). Only known areas are mapped; not all production areas are known. Production areas for mule deer are not mapped.

[9] https://cpw.state.co.us/learn/Maps/CPW-Public-GIS-Species-Activities-Definitions.pdf

- **Severe winter range**—that part of the range where 90 percent of the individuals are located when the annual snowpack is at its maximum and/or temperatures are at a minimum in the two worst winters out of ten.
- **Winter concentration areas**—that part of the winter range where densities are at least 200% greater than the surrounding winter range density during the average five winters out of ten from the first heavy snowfall to spring green-up.

We treated each activity area as equally important. Overlapping areas (within and between species) were merged and given a score of 1. In other words, overlapping areas did not count as more important.

Local Movement Corridors for Elk and Mule Deer

In recognition of the need for animals to be able to move within and among habitats, we developed a landscape permeability model for elk and mule deer to identify corridors that connect high quality areas, concentrating on movement within the transition area between summer and winter ranges. Note that these corridors represent areas that are likely necessary for functional habitat and do not represent long-distance migration. See Appendix I for detailed methods used to create the permeability layer.

We added CPW's SAM Migration Corridors that were contained entirely within the Watershed for both elk and mule deer. We then scored all corridors equally (value of 1); overlapping corridors had their ranks summed to highlight areas of connectivity shared between species. We determined that this difference in treatment of overlapping corridors compared to the treatment of overlapping SAM critical areas (above) was warranted because we did not want to unduly bias the final results toward winter habitat.

Anthropogenic Constraints in Movement Corridors for Elk and Mule Deer

We used our Landscape Disturbance Index (Appendix J) and aerial imagery to identify human-caused constrictions in movement corridors, which we named the "pinch points" layer (Figure L-1). We added concentrated areas of roadkill for elk and mule deer to the pinch points layer using data from Colorado Department of Transportation (CDOT) and Colorado State Patrol (CSP). These datasets did not include any points for Bighorn within the Watershed. Within the Watershed, CDOT roadkill data cover Highways 82 and 133 only, for the years 2013 – 2018. CSP roadkill data include highways as well as a few reports from local roads, for the years 2011 – 2018. However, we used only CSP points that were *not* on Highways 82 or 133 because of the difficulty in distinguishing whether or not these points were different than those in the CDOT data.

Each pinch point and roadkill report was assigned a severity rank of Low, Medium, or High. For the pinch points that we generated, severity ranking was based on the LDI model, with manual confirmation using aerial imagery. For roadkill data, severity ranking was based on recency of occurrence (i.e., 2018 reports counted more than 2013 reports) *and* the total number of animals (by species) reported killed at each mile marker over all the years, using the formula:

$$S = \frac{\sum_{i=1}^{n} m_i}{\frac{\sum_{i=1}^{n} \frac{(y_i - 2000)}{18}}{n}}$$

where: S = Severity Score, m_i = number of individuals of the same species recorded for the i^{th} record, n = total number of records at that mile-point, y = four-digit year of the date of report for the i^{th} record.

So, for example, a Severity Score of 1 equates to 1 animal killed at a particular location in 2018 only. For mule deer, the scores ranged from 0.7 – 24.9, and for elk from 0.7 – 4.4, with most scores falling on the lower end of the range. The scores were classified as Low: <= 1, Medium: > 1 – 5, and High: > 5.
To create the final pinch point layer, we created a kernel density estimate with the severity ranks and a 1 km search radius to combine all points into a smoothed weighted surface that highlights the most significant anthropogenic barriers to ungulate movement. The values of the kernel density (range 0 – 144) represent the estimated number per square kilometer per year of elk and deer blocked or killed while moving to seasonal habitat areas. In order to combine the kernel density with the other Key Areas inputs, we used the $\log_{10}$ of the value + 1. The value range of results was 0-2.16.

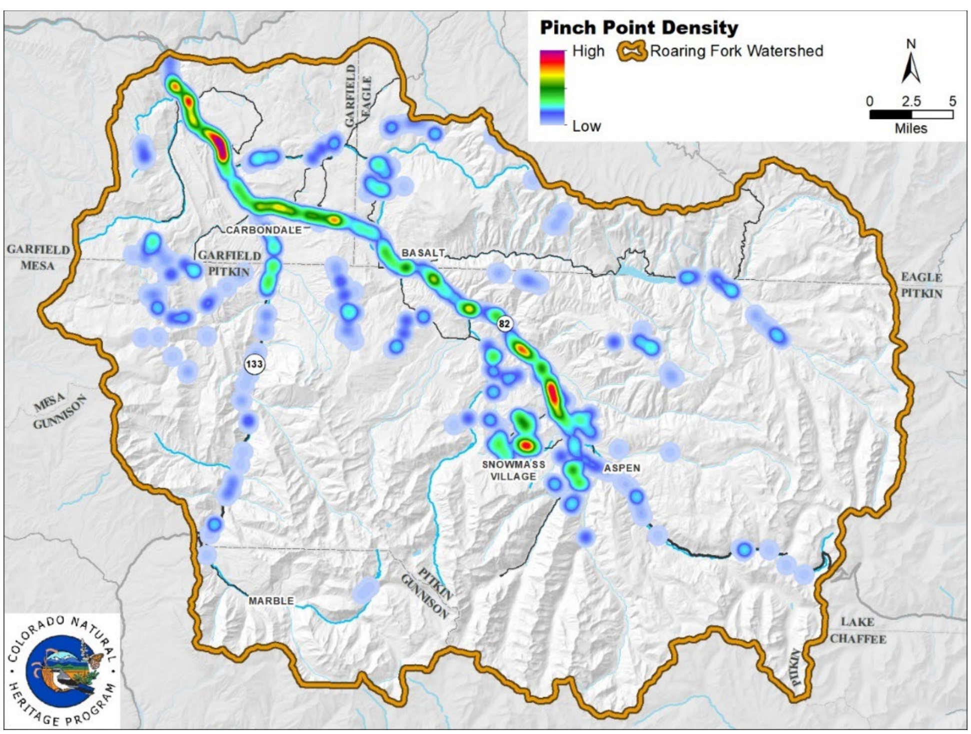

Figure L-1. Density of human-caused constrictions in movement corridors ("pinch points") in the Roaring Fork Watershed.

Ecological Pinch Points

We used The Nature Conservancy's (TNC's) Resilient and Connected Landscapes analysis (TNC-CRCS 2021) to incorporate climate change into our Conservation Importance layers. The underlying concept of their analysis was "conserving nature's stage" based on a metaphor where the physical environment is the stage and species are the actors. This concept is based on the understanding that species diversity is highly correlated with geophysical diversity (e.g., complexity of patterns in soils, geology, slope, aspect), and the assumption that species can take advantage of local microclimates to persist in the landscape under changing climate. Thus, conserving examples of all geophysical settings, and prioritizing those with the most microclimate diversity and highest landscape permeability, will maintain evolving ecosystems and biodiversity (though sites may contain different species in the future compared to now).

We used two attributes from the Resilient_and_Connected_Network layer (TNC-CRCS 2021) to represent ecological pinch points (where the landscape inhibits potential for population movements and range shifts) within areas that were otherwise resilient to impacts from climate change:

- **Resilient, Concentrated Flow,** given a score of 2.
- **Mostly Resilient, Concentrated Flow**, given a score of 1.

For our purposes, "flow" in this context can be interpreted as ability of animals to move through the landscape. "Concentrated Flow" refers to areas where large quantities of flow are concentrated through a narrow area.

To lessen the artifacts of the coarser resolution of some of TNC's inputs, we smoothed the input using a Focal Mean with a 200m radius moving window.

Sites of Local Significance

Two sites of local significance were suggested by the Science Team for inclusion in our Key Areas layer—Spring Park Reservoir Important Bird Area, North Star Nature Preserve, and Filoha Meadows Nature Preserve. Each of these sites was given a score of 1.

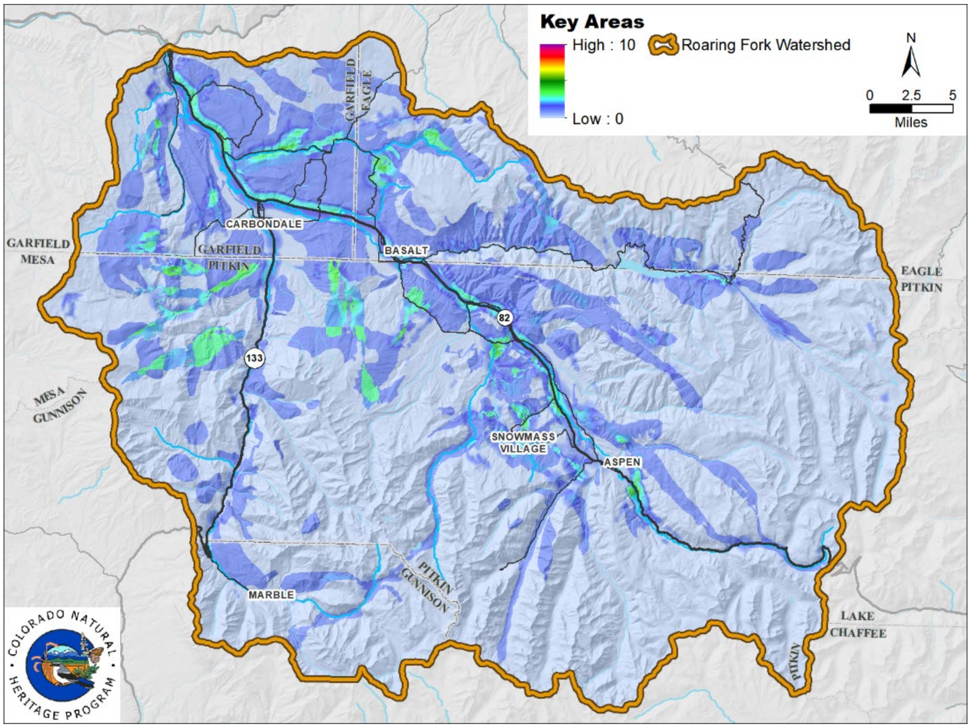

Figure L-2. Map of "Key Areas" in the Roaring Fork Watershed.

Biodiversity Importance

We used three data sources to create the Biodiversity Importance layer, as described below. All Biodiversity Importance scores were combined by taking the maximum value for any one area, and the whole smoothed with a 100m Focal Mean to compensate for any imprecision in the data. The range of scores was 1-10. The final Biodiversity Importance layer is shown in Figure L-3.

CNHP Element Occurrence Records

CNHP's Element Occurrence (EO) database contains records for documented locations of rare or imperiled species and plant communities (i.e., "elements of biodiversity"). Each species and plant community tracked by CNHP is assigned a Natural Heritage Imperilment Rank on a scale of 1-5, with 1 being critically imperiled, and 5 being demonstrably secure (defined in Table L-1). We used the 2021 database, and deleted all records that were not precise or recent. Thus, records for historic observations and extirpated locations were not included, nor were records where information was too general for reliable mapping of the location. Locations were generalized for records identified as sensitive and those with lower location precision (i.e., mappable within a square mile, but exact location uncertain). Biodiversity Importance scores were assigned based on Imperilment Rank at the state or global scale (whichever was most imperiled). Please note that an absence of Element Occurrence data in any particular area is *not* evidence of absence of biodiversity importance, and may be due to a lack of recent or reliable surveys of an area.

Table L-1. Colorado Natural Heritage Program imperilment ranks.

Natural Heritage Rank	Definition	Biodiversity Importance Score *
1	Critically Imperiled – critically imperiled because of extreme rarity or because of some factor(s) making it especially vulnerable to extirpation or extinction. Typically 5 or fewer occurrences or less than 1,000 remaining individuals.	10
2	Imperiled – imperiled because of rarity or because of some factor(s) making it very vulnerable to extirpation or extinction. Typically 6 to 20 occurrences or between 1,000 and 3,000 remaining individuals.	8
3	Vulnerable – vulnerable either because rare and uncommon, or found only in a restricted range (even if abundant at some locations), or because of other factor(s) making it vulnerable to extirpation or extinction. Typically 21 to 100 occurrences, or between 3,000 and 10,000 remaining individuals.	6
4	Apparently Secure – Uncommon but not rare, and usually widespread. Possible cause of long-term concern. Usually more than 100 occurrences and more than 10,000 remaining individuals.	4
5/U	Secure (5) – Common, widespread, and abundant. Perpetually secure under present conditions. Typically with considerably more than 100 occurrences and more than 10,000 individuals. Unranked (U) – rank not yet assessed.	2

* If the record was only mappable to a precision of about a mile (i.e., exact location not known), it was given Score – 1.

Wetlands

We used the updated wetlands layer for the Roaring Fork Watershed, created as part of an EPA-funded study being conducted by CNHP concurrent with this study (Marshall in prep). Wetlands were ranked as either 'Rare' or 'Support', defined and scored as:

- **Rare**: intersected Element Occurrences with Imperilment Rank of 1, 2, 3 at the state scale, given same scores as the EOs (Table L-1), *plus* all fens not otherwise included, which were given a score of 6.
- **Support**: all other wetlands that are not human modified (excavated, farmed, or impounded), or streams, given a score of 4. (Those stream segments with known biodiversity value are already included in the EO data).

Landscape Diversity

We used the "Landscape Diversity" layer (TNC-ECS 2020) within the TNC Resilient and Connected Network geodatabase to represent areas in the Watershed that would be resilient to impacts of climate change, according to the assumptions and methods of that analysis, where they identified the sites that scored above or below average in estimated resilience using the -0.5 standard deviations (SD) to +0.5 SD of the range of sites as the definition of average:

- **Most Resilient—**Far above average (>2 SD), given a score of 5
- **More Resilient—**Above average (1- 2 SD), given a score of 3

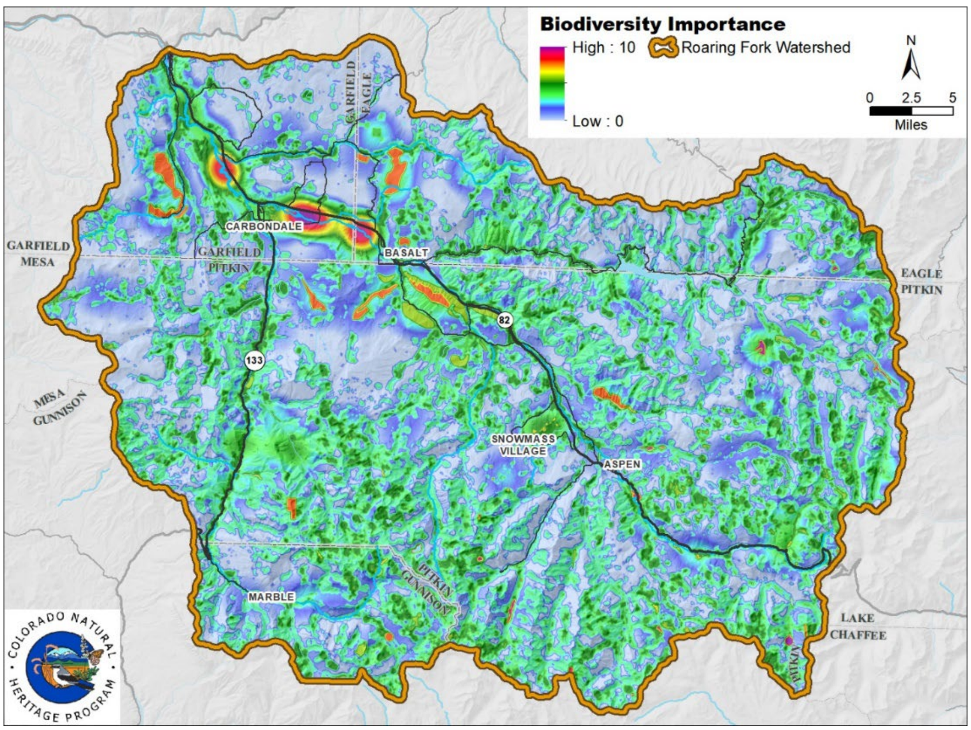

Figure L-3. Modeled biodiversity importance for the Roaring Fork Watershed.

Results

Conservation Importance (Figure L-4) scores are a sum of the Key Area score and the Biodiversity Importance score. Values ranged from 0 to 13. Final scores greater than 10 were treated as a 10. This is because overlapping values that exceed the maximum individual score of 10 are not "beyond the maximum important." They are simply of maximum importance. Please note these values are relative and unitless.

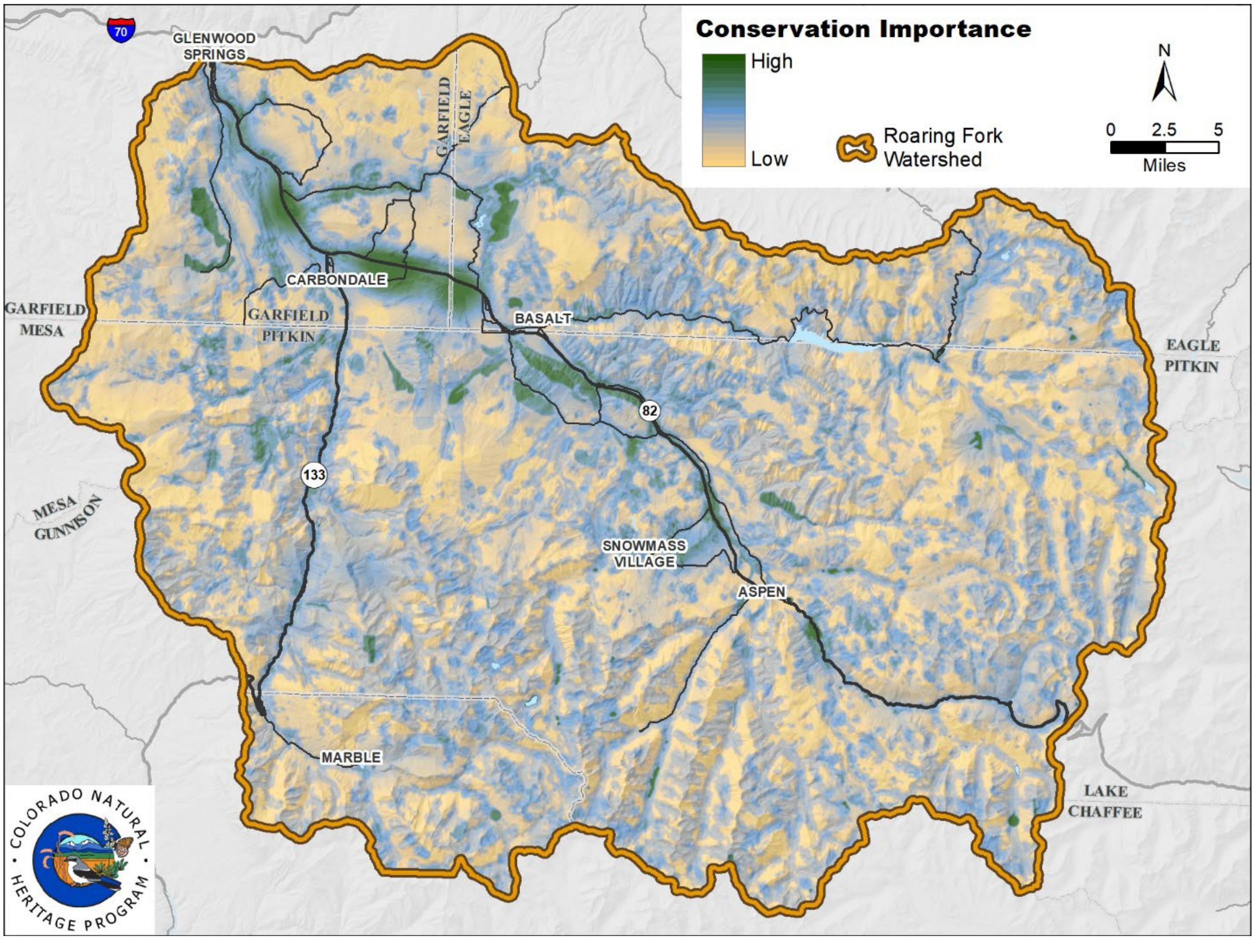

Figure L-4. Modeled conservation importance for the Roaring Fork Watershed.

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Definitions for SAM categories: https://cpw.state.co.us/learn/Maps/CPW-Public-GIS-Species-Activities-Definitions.pdf

APPENDIX M. CROSSWALK OF SWREGAP LAND COVER CATEGORIES TO ECOLOGICAL SYSTEMS

Ecological System	SWReGAP Land Cover Categories
Alpine	Rocky Mountain Alpine Fell-Field Rocky Mountain Dry Tundra
Aspen	Rocky Mountain Aspen Forest and Woodland
Oak/Mixed Shrub	Rocky Mountain Gambel Oak-Mixed Montane Shrubland Rocky Mountain Lower Montane-Foothill Shrubland
Pinyon-Juniper	Colorado Plateau Mixed Bedrock Canyon and Tableland Colorado Plateau Pinyon-Juniper Shrubland Colorado Plateau Pinyon-Juniper Woodland Recently Chained Pinyon-Juniper Areas Southern Rocky Mountain Pinyon-Juniper Woodland
Sagebrush	Inter-Mountain Basins Big Sagebrush Shrubland Inter-Mountain Basins Greasewood Flat Inter-Mountain Basins Mat Saltbush Shrubland Inter-Mountain Basins Mixed Salt Desert Scrub Inter-Mountain Basins Montane Sagebrush Steppe Inter-Mountain Basins Semi-Desert Shrub Steppe
Spruce-Fir	Recently Logged Areas Rocky Mountain Cliff and Canyon Rocky Mountain Subalpine Dry-Mesic Spruce-Fir Forest and Woodland Rocky Mountain Subalpine Mesic Spruce-Fir Forest and Woodland
Other/Mixed Conifer	Inter-Mountain West Aspen-Mixed Conifer Forest and Woodland Complex Recently Burned Rocky Mountain Lodgepole Pine Forest Rocky Mountain Montane Dry-Mesic Mixed Conifer Forest and Woodland Rocky Mountain Montane Mesic Mixed Conifer Forest and Woodland Rocky Mountain Ponderosa Pine Woodland Rocky Mountain Subalpine-Montane Limber-Bristlecone Pine Woodland
Wooded Riparian	Rocky Mountain Lower Montane Riparian Woodland and Shrubland Rocky Mountain Subalpine-Montane Riparian Shrubland Rocky Mountain Subalpine-Montane Riparian Woodland
Wetland	North American Arid West Emergent Marsh Open Water Rocky Mountain Alpine-Montane Wet Meadow
Montane Meadow	Rocky Mountain Subalpine Mesic Meadow Southern Rocky Mountain Montane-Subalpine Grassland

Ecological System	SWReGAP Land Cover Categories
Agriculture	Agriculture Invasive Annual and Biennial Forbland Invasive Annual Grassland Invasive Perennial Forbland Invasive Perennial Grassland
Developed/Disturbed	Barren Lands, Non-specific Developed, Medium - High Intensity Developed, Open Space - Low Intensity Inter-Mountain Basins Active and Stabilized Dune Recently Mined or Quarried
Grassland	Inter-Mountain Basins Semi-Desert Grassland
Rock/Ice	Rocky Mountain Alpine Bedrock and Scree

Notes:

1. It was not possible to include a given land cover category in more than one ecological system. Recently Logged, Recently Burned, and Rocky Mountain Cliff and Canyon were assigned to the ecological system in which the majority of those polygons occurred. The biggest areas marked 'burned' were in Other/Mixed Conifer, and the biggest areas marked 'logged' were in Spruce-Fir. Cliff & Canyon was likewise primarily in the Spruce-Fir. These cover a very small proportion of the watershed, and in the case of burned and logged areas the data are outdated (~2004) and not reflective of more recent events.
2. Some categories (e.g., sand dunes) don't exist in the watershed at all, but were listed in the layer's attributes.
3. Rock/Ice is 'Not Habitat' in the Forage and Habitat Quality models. Alpine only includes the vegetated lands, as mapped by the land cover layer.

APPENDIX N: IMPORTANT SECONDARY SPECIES AND GROUPS IDENTIFIED BY STAKEHOLDERS

Contributed by Tom Cardamone, Watershed Biodiversity Initiative

In 2018 the Science Team that framed and then guided the Biodiversity Study was encouraged by internal and external stakeholders to include species beyond the three focal species the Science Team ultimately determined as foundational to the Study: elk, mule deer, and bighorn sheep. Those other species and groups were birds, black bear, beaver, and insect pollinators.

Once the focal and other animal categories were established, WBI entered discussions with the Colorado Natural Heritage Program about conducting the Biodiversity Study in our million-acre watershed within a two-year period with a set budget. These practical considerations led to an agreement with CSU/CNHP that their focus for Study would be limited to the three focal species identified by the Science Team (elk, deer, and bighorn sheep). These three species were recognized as proxies that would generally accommodate the habitat needs of much of the existing biodiversity in the watershed. WBI committed to a best effort approach to including the secondary species/groups by recruiting other organizations and individuals to contribute the secondary elements to the Study. Early on it was understood that coverage of these secondary elements would necessarily be limited by the capacity of others to provide the science, and the existing dearth of science specific to the Roaring Fork Watershed compared to the abundance of science already in place for elk, deer, and bighorn sheep.

The secondary species/groups were eclipsed by the demands of the Biodiversity Study. Nonetheless, they warrant inclusion in an appendix of the Study as a placeholder and reminder that existing science and future studies can serve to amplify the importance and usefulness of the Roaring Fork Watershed Biodiversity and Connectivity Study. The secondary elements also serve to underscore the idea that while the Biodiversity Study's foundation is its focus on three species, the Study's intent is to provide science that leads to the protection and restoration of the full complement of biodiversity within the Roaring Fork Watershed.

BIRDS

More than half of the 500+ species of birds found in Colorado occur in the Roaring Fork Watershed. For better than half a century the Roaring Fork chapter of the National Audubon Society has organized the watershed's Christmas Bird Count and a spring/summer Breeding Bird Survey. The data collected have contributed to an understanding of bird populations statewide and on a continental scale. Arvind Panjabi is a scientist at CSU and an author of "Decline of the North American Avifauna" published in the journal Science in 2019 (Rosenberg et al. 2019).

The primary findings reported in the paper are that bird numbers in North America have declined by 2.9 billion, or 29%, since 1970 due to habitat loss, habitat degradation, and to a lesser degree, cats (2.6 billion/year) and windows and other structures (900 million/year). Interestingly, 90% of the decline is within sparrows, warblers, finches, and swallows. Since 1970, waterfowl have increased 56% and hawks and eagles have increased by 78%.

In the report, Panjabi writes; "We have models for success, but we're lacking resources. We as a country need to decide whether we're going to invest in the conservation of our ecosystems." The Biodiversity Study that identifies the best opportunities for habitat restoration in the Roaring Fork Watershed provides a blueprint for bird conservation in our million-acre backyard.

References

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BLACK BEAR

Forty years ago, wildlife managers in Colorado, informed by a long-term bear study by Colorado Division of Wildlife bear biologist Tom Beck, were concerned about declining bear populations marked by unbalanced age distribution, with too few mature adult animals compared to young age classes. This led to the end of the Spring Bear hunt and baiting of bears with a goal of restoring vitality to bear populations.

Today, particularly in years when serviceberry, chokecherry, and acorn crops in the mountain shrublands are poor, there seem to be bears in every community rummaging for crabapples and human trash. Black bears were identified for the Study because of the correlation of bear-human conflicts with weather and climate-driven wild food shortages.

Studies in the Watershed and elsewhere have shown bears to roam widely in search of natural food sources and to thrive best in large, un-fragmented habitat swaths. Although further study is warranted, it is reasonable to conclude that if bears are able to roam freely and widely to access food resources, particularly in their period of hyperphagia (gorging) from mid-August until hibernation in late fall, the bears will thrive and conflicts with humans will be reduced.

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Columbia. Appendix G: American black bear. Climate Impacts Group, University of Washington. https://cig.uw.edu/wp-content/uploads/sites/2/2014/11/Appendix20G.20Black20Bear.compressed.pdf.

BEAVER

This species is referenced in CNHP's EPA-funded wetland study (Marshall in prep), which recognizes the important role of beaver in maintaining and creating wetlands. The wetland study also includes mapping of the most accommodating sections of all the watercourses in the Watershed for beaver reintroduction to enhance the percentage of the watershed classified as wetlands. This mapping is produced by a model known as the Beaver Restoration Analysis Tool (BRAT).

Seventy-five percent of all native nesting bird species and eighty percent of all native wildlife species depend on riparian and wetland ecosystems for at least part of their life cycle. Beaver, as wetland creators and riparian health contributors, are clearly very important to the protection and restoration of biodiversity in the Watershed's landscape. The mapping produced by the biodiversity study allows for the merging of the BRAT with the Landscape Disturbance Index (LDI; see Appendix J of this report) in order to accurately identify appropriate areas for beaver restoration and to avoid those areas where conflicts with human activities may be unacceptable.

The following links are to compelling video presentations and articles that illustrate and characterize the significant capacity of beaver to increase the wetness of the Roaring Fork Watershed. They show, in terms of wetland acreage and natural water capture and storage capacity (both surface water and ground water), what the enhancement of existing beaver populations in appropriate locations could contribute to the "wetness" that translates directly into biodiversity richness, and indirectly into wildfire suppression and resilience.

- "Idaho Rancher Jay Wilde Restores Beaver to Birch Creek in a Big Way! YouTube (https://www.youtube.com/watch?v=K_2Ib0pQYPo)
- "Dam It: Why Beavers Matter" YouTube (https://www.youtube.com/watch?v=5pk_VD1-8BM)
- "Beavers are Back in a Conservation Success Story" www.nationalgeographic.com
- Beaver Restoration Analysis Tool (BRAT) https://cnhp.colostate.edu/cwic/tools/toolbox/ and https://csurams.maps.arcgis.com

BUMBLE BEES and BUTTERFLIES

*"Fifty percent of the animal individuals that once shared the Earth with us are already gone."**

Stakeholders identified bumble bees and butterflies as proxies for insect pollinators and insects generally. Insects comprise two-thirds of all terrestrial animal species and they are essential to the proper functioning of all ecosystems. Insects are food for other animals, pollinators, pest-controllers, and nutrient recyclers. Given these critical roles, it is alarming to note that globally 41% of insect species are in decline, 31% are threatened, and 10% are locally going extinct. This extinction rate is eight times the rate for mammals, birds, and reptiles. Consider the honeybees: In the U.S., honeybee colonies declined 41% from 1947 to 2007. Pollinator declines jeopardize 35% of the global food supply for humans.

The numbers are elusive and do vary from study to study, yet the trend is clear. The millions of insect species that together are indispensable to life on Earth (whether it is two or thirty million species) are in dramatic decline, imperiling life. Agricultural practices including natural habitat loss and pesticide use are thought to be the primary cause of the decline. Yet in Puerto Rico, where pesticide use has declined 80% since 1969, insect biomass has decreased 75% - 88% from 1976 to 2018. Increasing temperatures and drought may be the cause there. Climate change is widely recognized as a secondary cause of insect declines, and seems to be the primary cause in Puerto Rico.

Just south our watershed at the Rocky Mountain Biological Lab in Gothic, Colorado, a thirty four-year study in the subalpine has found a dramatic decline in insects (1986-2019). There, insect biomass has declined 35.9% and abundance (number of species) has declined 60.4%. These declines correlate with climate change, specifically less rain and snow years, and to a lesser degree, warmer temperatures. Land use practices and habitat loss are not factors in the subalpine around Gothic. The effect of temperature is unsurprising, since it is known that temperature increases are amplified in mountain environments.

The Independence Pass Foundation in consultation with scientists at RMBL has initiated (in 2019) a pollinator study transect from Aspen to Independence Pass. IPF is collecting data on pollinators at five locations from 8,000 to 12,000 feet elevation with particular attention to bumblebees and butterflies. In time the data IPF collects can be compared to RMBL data and will provide important science regarding the condition of pollinators in the Roaring Fork Watershed.

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The Washington Post. https://www.washingtonpost.com/science/2018/10/15/hyperalarming-study-shows-massive-insect-loss/?noredirect=on&utm_term=.405441d7ee90

Smithsonian Institution. https://www.si.edu/spotlight/buginfo/bugnos