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# Landscape Planning for Climate Change Resilience in the Southern Rockies

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LANDSCAPE PLANNING FOR CLIMATE CHANGE RESILIENCE IN  
THE SOUTHERN ROCKIES

by

Jeffrey D. Haight

A thesis submitted in partial fulfillment  
of the requirements for the degree

of

MASTER OF SCIENCE

in

Ecology

Approved:

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2018

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## ABSTRACT

## Landscape Planning for Climate Change

## Resilience in the Southern Rockies

by

Jeffrey D. Haight

Utah State University, 2018

Major Professor: Edward Hammill  
Department: Watershed Sciences

Climate change is impacting natural systems with unprecedented intensity, widely altering the physiology and ecology of species, communities, and ecosystems that are of concern to conservation. While efforts to protect these diverse ecological resources across broad landscapes already exist, the success of those efforts will depend in part on their ability to help buffer against the impacts of climate change. Doing so first requires knowledge of landscape factors that contribute to the resilience of regional biodiversity, particularly those influencing the ability to adapt to climate shifts. Within the context of landscape conservation, those factors often take two key forms: areas with minimal exposure and vulnerability to climate shifts (climate refugia) and areas critical for connecting populations across the landscape (connectivity corridors). Though robust methods for assessing climate refugia and corridors have already been developed, they have typically been applied on a case-by-case basis for individual species or ecosystems. Unfortunately, this individualized strategy is unfeasible and inefficient across the highly

biodiverse regional scales at which much conservation planning occurs. Furthermore, actions to maximize resilience to climate change impacts cannot continue to ignore the wider range of socioecological factors that threaten species persistence, such as human land development. In this thesis, I have explored how coarse-filter metrics associated with climate change resilience could be systematically integrated into existing systems for protected area conservation, using the Southern Rockies Landscape Conservation Cooperative as a case study. I first modeled climate change exposure and connectivity throughout the region, identifying the areas that are generally less vulnerable to climate change impacts. I then used these metrics as the basis for simulating the priority of protecting certain areas as either climate refugia or corridors that also house multiple species in need of conservation. Initial evaluation of climate change exposure and connectivity revealed consistent patterns in climate vulnerability that varied considerably across the region, providing a robust foundation for prioritizing conservation actions. By subsequently combining these metrics with the distributions of threatened species and other ecological resources of interest, climate change impacts can drive landscape conservation decisions in a manner that still aligns with ongoing management needs and objectives. This work highlights that adequately protecting ecological resources from the pressures of climate change will require more thorough spatial assessment of additional factors contributing to the success of conservation efforts, especially those related to human actions. I believe that the strategies for spatial prioritization I have outlined provide landscape managers with a framework for explicitly basing their decisions on climate change in a manner that accounts for wider conservation objectives, limitations, and needs.

(88 pages)

## PUBLIC ABSTRACT

### Landscape Planning for Climate Change

#### Resilience in the Southern Rockies

Jeffrey D. Haight

The unique species, ecosystems and landscapes of the Western United States are experiencing unprecedented pressures from climate change, creating new challenges for conservation. As temperatures rise and patterns of precipitation shift, plant and wildlife species have been shifting their ranges to new areas in search of more suitable climates, building groupings of species that are historically unfamiliar. These climate-driven migrations place an additional burden on species that are already threatened from habitat loss and other human-related activities. The impacts of climate change are of particular concern in landscapes that have long been conserved and managed based on the ecological features that define them, including national parks, wildlife refuges, and wilderness areas. With many of these existing protected areas experiencing ecological shifts due to climate change, there is a growing need to identify the places within wider regions that will help species cope with impacts of changing climatic conditions. In some cases, those places are those where the pressures of climate change are least pronounced, what are referred to as “climate refugia.” At other times, helping plants and wildlife cope involves aiding their movement across the landscape in response to climate shifts, by preserving the connectivity between critical habitats and other highly important areas. While many efforts have been made to assess the potential of different areas as climate refugia and corridors, these practices have usually been carried out looking at individual species or ecosystems at a relatively local scale. Unfortunately, many of the decisions to

conserve new parts of the landscape occur across much broader regions that span a multitude of species and ecosystems, ranging from individual states to entire continents. As a consequence, assessing climate refugia and corridors on a case-by-case basis for every ecological feature is neither feasible nor an efficient use of the limited resources available for conservation. Additionally, when deciding which areas are best suited for protecting native species and ecosystems from the impacts of climate change, one cannot ignore the existence of the other prevalent threats to conservation, such as habitat loss or invasive species. In this thesis, I have explored methods for widely incorporating climate change into the complex process of identifying high priority areas for conservation across broad regions. As a case study for this work, I chose the Southern Rockies Landscape Conservation Cooperative, a collaborative public and private effort for conserving and managing the ecological characteristics of a distinct region spanning seven states in the US Intermountain West. After broadly measuring climate change impact and connectivity in a manner that was not tied to any particular species, I simulated climate refugia and corridors that simultaneously represented the ranges of 31 separate wildlife species. Though further research is needed to better understand the full suite of threats to species persistence, the means already exist for conservation decision makers to account for climate change in their actions. I believe that my work supports that decision making process, providing a framework for identifying areas that are most critical for aiding diverse species and ecosystems in their responses to the pressures of climate change.

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I could not have asked for a better group of people to guide me through this research experience. I would like to start off by giving special thanks to my major advisor, Dr. Edd Hammill, for providing with this opportunity and for being my mentor and role model. I am hugely grateful for his unwavering positive guidance, for reminding me to remain confident in my work, and for showing me how to enjoy living the life of a scientist. Many thanks also go to my two committee members, Drs. Tom Edwards and Jacopo Baggio, whose instruction and advice will I take with me wherever I may end up.

I extend additional appreciation to my numerous other colleagues, research collaborators, and funders who made this work possible in the first place. At the Utah Division of Wildlife Resources and The Nature Conservancy, in particular, Jimi Gragg, Eric Edgley, Stephen Hansen, and Joel Tuhy provided financial support and gave me a vital sounding board for the research ideas in this thesis. Extra thanks to the support from the USU Climate Adaptation Science fellowship program, the Ecology Center, and the students and faculty in both, who have all greatly enriched my experience. Lastly, thank you to the Department of Watershed Sciences, for being one of the best academic communities around.

Of course, I truly could not have done any of this without the constant support of my friends and family, near and far. Thank you to my friends; not only did you help keep me sane through this endeavor, but you made the last couple of years a blast. We have had adventure after awesome adventure and fantastic conversations, both intellectually stimulating and remarkably ridiculous. I look forward to having much more of both in the future. Finally, a thousand thanks to my family for the lifetime of love and support that

has laid the foundation for all my accomplishments. I hope that I have made you proud.

Jeffrey Haight

## CONTENTS

	Page
ABSTRACT .....	iii
PUBLIC ABSTRACT .....	v
ACKNOWLEDGMENTS .....	vii
LIST OF TABLES .....	x
LIST OF FIGURES .....	xi
CHAPTER	
1. INTRODUCTION .....	1
2. QUANTIFYING METRICS OF CLIMATIC RESILIENCE WITHIN THE STATE OF UTAH .....	14
3. IDENTIFYING POTENTIAL CLIMATE REFUGIA FOR CONSERVATION ON THE BASIS OF ASSESSED CLIMATE VULNERABILITIES .....	41
4. SUMMARY AND CONCLUSION .....	62
REFERENCES .....	66
APPENDICES .....	74

LIST OF TABLES

Table		Page
1	Protected Area Coverage in the Southern Rockies Region .....	13
2	Marxan parameters for each conservation scenario.....	51

## LIST OF FIGURES

Figure		Page
1	Spatial Extent of the Southern Rockies Landscape Conservation Cooperative in the Western United States .....	10
2	EPA Level III Ecoregions of the Southern Rockies LCC .....	11
3	Protected areas of the Southern Rockies LCC .....	12
4	Modeling domain and inputs for climate connectivity mapping .....	23
5	Sensitivity of climate velocity estimates to a range of climate match thresholds, based on a) mean annual temperature and b) mean annual precipitation.....	26
6	Relative forward climate velocities in the Southern Rockies under four climate projections, calculated using changes in mean annual temperature alone .....	27
7	Quantile pattern comparison between the two most similar maps of climate velocity based on mean annual temperature (2050s RCP 8.5 and 2080s RCP 4.5) .....	27
8	Relative forward climate velocities in the Southern Rockies under four climate projections, calculated using changes in mean annual precipitation alone .....	29
9	Quantile pattern comparison between the two most similar maps of climate velocity based on mean annual precipitation (2050s RCP 4.5 and 2080s RCP 4.5) .....	30
10	Mean climate velocities for the Southern Rockies calculated using different climate metrics .....	30
11	Analog-based climate velocities based on a) mean annual temperature, b) mean annual precipitation, and c) a multiplicative combination of both climate metrics .....	32
12	Similarity between climate velocity patterns generated using contrasting metrics a) temperature vs. precipitation, b) temperature vs. multivariate, and c) precipitation vs. multivariate.....	33
13	Modeled climate corridors under present climate conditions .....	35

14	Least-cost paths (corridors) by efficiency, represented using the ratio between cost-weighted distance (CWD) and the Euclidean distance of the path.....	36
15	Overall in climate-based movement costs between present and projected future conditions (2050 RCP 4.5) .....	37
16	Proportional changes in climate connectivity between present and projected future conditions (2050 RCP 4.5) .....	38
17	Spatial distributions of four Marxan inputs: a) conservation targets (species of concern), b) risk (human land modification), c) climate exposure, and d) climate connectivity.....	50
18	Marxan outputs for conservation scenario #1 for minimizing climate exposure: a) selection frequency and b) least-exposure run solution .....	53
19	Marxan outputs for conservation scenario #2 for maximizing climate connectivity: a) selection frequency and b) most-connectivity run solution .....	54
20	Adjoining high priority areas (climate corridors and climate refugia) .....	55
21	Change in conservation priority (selection frequency) when accounting for risk and ignoring risk in scenarios for a) minimizing climate exposure and b) maximizing connectivity .....	56
22	Optimal climate refugia distribution relative to currently protected planning units.....	57
23	Protected planning unit characteristics versus the entire Southern Rockies region, comparing a) climate exposure and b) modeled conservation priority .....	57
24	The a) exposure cost and b) modeled conservation priority of the 50 largest contiguous protected areas, each over 250 km <sup>2</sup> .....	58

# CHAPTER 1

## INTRODUCTION

Natural systems are experiencing unprecedented pressures from never before experienced rates of climate change. As patterns in climatic conditions shift and intensify, species and ecosystems around the world have already started to respond physiologically and ecologically to these changes (Walther *et al.*, 2002). These numerous responses include changes in species phenology (Parmesan & Yohe, 2003), restructuring of community composition (Brown *et al.*, 1997), and altitudinal and latitudinal shifts in species ranges (Harsch *et al.*, 2009; Chen *et al.*, 2011). Furthermore, the impact of climatic changes are not uniformly distributed across the landscape, varying along with physiographical and ecological patterns such as latitude, altitude, and vegetation cover (IPCC, 2014). Due in part to this heterogeneity of climate change impact, managers of protected natural systems are confronted with the challenge of conserving species, ecosystems, and other biological resources in an uncertain and rapidly changing world.

While current practices in global conservation continue to mandate the identification and protection of areas primarily for their biological value, it has been increasingly recommended that these conservation paradigms be adapted to explicitly account for the impacts of climatic change (Hannah *et al.*, 2002a; Heller & Zavaleta, 2008; CBD, 2016a, 2016b). However, in practice, the decisions made in designating areas for conservation are still largely driven by the representation of current, static ecological features, such as current species ranges or habitat types (Pressey *et al.*, 2007; Jones *et al.*, 2016). This process has often failed to take into account the dynamic biophysical nature of these systems, ignoring both their past and future proclivities for

change (Game et al., 2011; Ban et al., 2012). Thus, many such conservation decisions aimed at protecting natural resources from the risks associated with climate change have focused on current aspects of the landscape – such as connectivity – rather than integrating systematic assessments of future vulnerability.

Adapting the conservation and management of natural systems in light of global change requires the promotion of ecological resilience across multiple scales. Many interpretations of the term “resilience” have been put forward with respect to the study of social-ecological systems, with the majority being modified from the definition presented by C.S. Holling in his 1973 seminal paper (Holling, 1973; Chapin *et al.*, 2009). Of all the resilience definitions, one of the most useful for natural resource conservation comes from a more recent paper that describes resilience as “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks” (Walker *et al.*, 2004). Within the broad landscape context of biological conservation, the diversities of ecosystems, communities, species, and populations are all frequently portrayed as essential components of a region’s social-ecological structure and identity, thus warranting efforts for their conservation. In the face of ongoing disturbances associated with climate change and habitat fragmentation, the success of broad conservation efforts depends upon the ability of those ecological components to adapt while maintaining their fundamental characteristics. Efforts to protect regional biodiversity must work toward increasing adaptability, and thus resilience, across broad landscapes (Folke *et al.*, 2010; Oliver *et al.*, 2015). One can partially do this by initiating protection measures that facilitate the ability of species and ecosystems to change their distributions, minimizing their vulnerability to

climate shifts.

In the field of conservation planning for climate change resilience, the broadest level of decision making takes place when determining where and how to implement a few key strategies for minimizing the overall impact of climate changes (Lawler, 2009; Game *et al.*, 2011; Jones *et al.*, 2016). The first of these strategies has been to promote resilience simply by preserving areas across diverse geophysical settings, such as broad elevational and latitudinal gradients (Lawler, 2009). By protecting landscapes with heterogeneous topography and geology, one captures much of the variation in climatic and edaphic characteristics, providing organisms with the conditions necessary for them to shift and adapt to variably shifting climates. Another major strategy of adaptation-minded conservation targets the expansion of protected areas to incorporate climate change refugia (Ashcroft, 2010; Gonzalez *et al.*, 2010; Morelli *et al.*, 2016). These refugia serve as areas relatively buffered from climate impacts, enabling the persistence of physical, ecological, and cultural resources. Rather than simply aim to maintain a series of different refugia, a third main adaptation strategy involves enhancing landscape connectivity. It is generally supported that the ability for organisms to move easily across landscapes enhances the capacity for species to adapt to uncertain climatic changes and their impacts (Heller & Zavaleta, 2008; Hannah, 2011; Beier, 2012).

While numerous robust methods for quantifying climate vulnerability exist, generalizable data on climatic sensitivities and adaptive capacities that can be applied across multiple species and ecosystems are frequently lacking. Thus, especially when operating on broad scales that span multiple distinct ecological features, estimating climate vulnerability primarily involves measuring climate exposure. Using climate

model projections that depict potential changes in temperature, precipitation, and other biologically important climate metrics, one can derive simple approximations of climate exposure based on overall magnitudes of change, such as increases in averaged temperature variables (Parmesan & Yohe, 2003; Taylor *et al.*, 2012a). However, other methods for explicitly quantifying the intensity of climate change, such as the velocity of climate change (hereafter “climate velocity”), can increase the biological-relevance of abiotic climate exposure assessments (Loarie *et al.*, 2009; Corlett & Westcott, 2013; Burrows *et al.*, 2014; Carroll *et al.*, 2015). Climate velocity represents the minimum speed at which an organism living in a certain area would theoretically have to travel in order to maintain constant climate conditions in the future, given some projected long-term shift in climate parameters (Loarie *et al.*, 2009). While values of climate velocity can be used as proxy measures of climate exposure for identifying potential climate refugia, it is important to recognize that such abiotic measures ignore the actual presence of ecological features of interest to conservation, including the distributions of threatened species, cultural resources, and landscape facets (Morelli *et al.*, 2016; Carroll *et al.*, 2017).

In efforts to reduce ecological vulnerabilities to climate shifts, the broad ability of individual species to move across current and potential future landscapes – i.e. landscape connectivity – must additionally be quantified, maintained, and enhanced (Heller & Zavaleta, 2008; Beier, 2012). The importance of landscape connectivity for keeping species, populations, communities, and ecosystems robust to the impacts of environmental change has been readily observed across many systems (Tischendorf & Fahrig, 2000a, 2000b; Prugh *et al.*, 2008; Taylor *et al.*, 2012b; Ayram *et al.*, 2016).

Particularly for species characterized by metapopulation dynamics and those that undergo seasonal migrations as part of their life strategies, the ability to move across the landscape relatively unimpeded is often critical to maintaining stable populations (Taylor *et al.*, 2012b). It is further suggested that conservation focused on facilitating climate change-driven species range shifts should prioritize enhancing connectivity within corridors following climatic gradients (Beier, 2012). As a consequence of the critical roles that landscape connectivity has been shown to play in enabling species persistence, the improvement of connectivity has been one of the most frequently recommended practices for conservation in the field (Heller & Zavaleta, 2008). However, an action gap exists between advocacy for connectivity enhancement and the actual pursuit of connectivity-based conservation goals, as evidenced by the lack of specific and explicit connectivity objectives in the Wildlife Action Plans of many U.S. wildlife management agencies (Lacher & Wilkerson, 2013). In order to narrow this gap and promote the resilience of species and ecosystems to the uncertain impacts of climate change, greater efforts need to be made to directly incorporate assessments of connectivity in landscape planning processes.

While data describing climate exposure and connectivity can prove informative for guiding conservation actions on their own, efficient climate-driven conservation decision making requires structured efforts to integrate these data with a wider array of biophysical and sociopolitical factors (Game *et al.*, 2013). Enhancing the climate resilience of biologically-diverse systems requires widespread efforts to minimize climate vulnerabilities across regions of multiple scales, ranging from individual watersheds to entire continents. However, limitations on the resources available for conservation and

conflicts between competing management priorities typically make it unfeasible and unrealistic to provide protections to all the least-vulnerable areas within any given landscape. This forces managers to make tough decisions about where to prioritize the allocation of limited resources, decisions often based on current management needs and constraints rather than potential climate change vulnerabilities. While one can carry out this process of selecting priority areas through a variety of methods, such as the consultation of expert opinions, personal biases with respect to the direction of management actions may produce inefficient paths for meeting conservation objectives.

As an alternative method to expert-led decision making process, systematic landscape management (SLM) approaches can be utilized to improve the efficiency and efficacy of spatial conservation efforts (Wilson et al. 2006). Systematic spatial prioritization tools based on the concept of landscape complementarity, such as the software program Marxan (Ball et al. 2009), are particularly suited for this task of identifying of priority areas for conservation. These SLM strategies can be applied toward achieving a variety of conservation goals, such as the protection of threatened species or ecosystems. With Marxan in particular, this is done through an iterative process that selects areas (“planning units”) that capture the spatial distribution of one’s predefined conservation targets (e.g. species ranges) while also minimizing some “cost” value across the landscape. This process produces networks of priority protected areas characterized by a near-optimum balance between competing costs and conservation goals. While the cost variable to be minimized in this model is frequently an economic cost of restoring and managing the areas identified, one can alternatively seek to minimize other values, such as the ecological “cost” of being more vulnerable to climate

shifts. Marxan further enables the conservation practitioner to directly incorporate a broader suite of relevant biophysical and sociopolitical factors through the inclusion of risk, the probability of a potential protected area failing to protect its targets.

Despite the versatility of SLM approaches and their potential for reconciling competing interests in conservation efforts aimed at enhancing climate change resilience, relatively little work has yet been done to explicitly address climate change impacts and uncertainties in the field of systematic conservation prioritization (Jones *et al.*, 2016). Furthermore, very little climate-minded spatial prioritization research has addressed human responses to climate change - such as land use changes driven by climate, and their direct and indirect influences on conservation success (Faleiro *et al.*, 2013; Chapman *et al.*, 2014; Jones *et al.*, 2016). Given the ubiquitous roles that human actions play in the viability of ecological systems, efforts to effectively conserve natural resources in the face of climate change must continue to recognize the presence of people. Strategies for SLM can adapt robust decision making frameworks for targeting the protection of regional biodiversity in the face of widespread and rapid environmental change.

Here I test the utility of spatial prioritization techniques for streamlining the broad-scale conservation planning process in a manner that explicitly accounts for multiple overlapping objectives, especially reduction of highly variable climate change risks. Beginning in Chapter 2, I quantify broad metrics of climate change vulnerability across my study region using two main metrics: climate velocity and climate gradient connectivity. This fundamental assessment of vulnerability provides the basis for proceeding with conservation prioritization driven by spatial heterogeneity in climate

impact. In Chapter 3, I use a Marxan decision framework to combine my vulnerability estimates with threatened species ranges, existing protected areas, and land use risks. The aim of the third Chapter is to spatially prioritize new areas based on their capacity for maximizing regional resilience to climate shifts, and to assess the potential for existing protected areas to withstand the dynamic impacts of climate change. I hope that the decision making framework I describe will provide conservation practitioners with the means to systematically and dynamically integrate ecological assessments of climate vulnerability with the various social, economic, and political factors that also contributing to long-term environmental resilience.

### *Study Region*

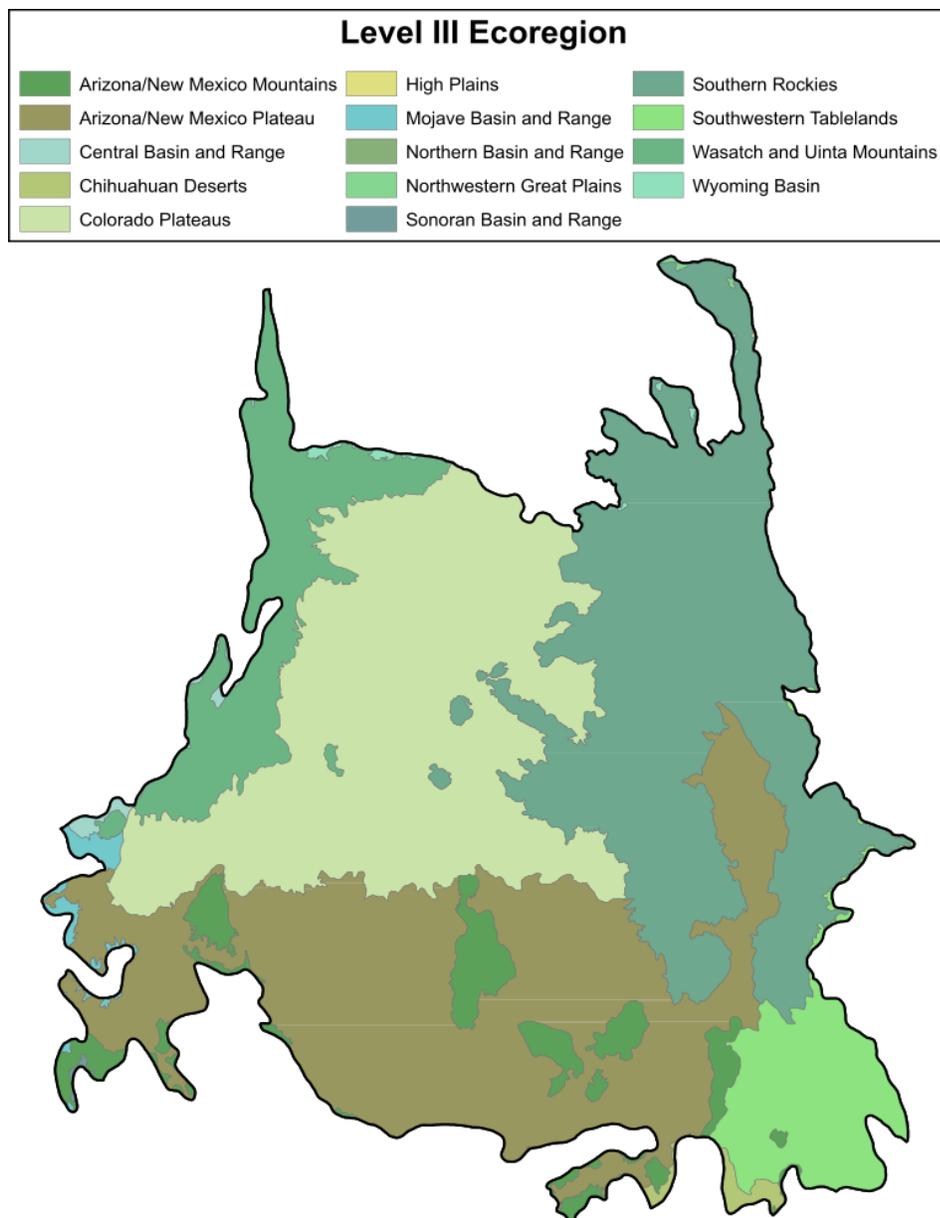
For the purposes of this study, I conducted my analyses across the entire landscape of the Southern Rockies region, as delineated by the Southern Rockies Landscape Conservation Cooperative (Figure 1; Southern Rockies Landscape Conservation Cooperative, 2018). The Landscape Conservation Cooperatives (LCC) Network is an association of 22 landscape-scale collaborative partnerships between governmental and non-governmental agencies and stakeholders that aim to address conservation issues crossing jurisdictional boundaries within regions of broad ecological similarity (Landscape Conservation Cooperatives, 2014). The ecologically-defined extent and broad scale of these interdisciplinary endeavors also makes them particularly applicable as regions for the practice of climate-driven systematic landscape management. As one of these partnerships, the Southern Rockies LCC was established for the collective conservation and management of a vast, topographically diverse region spanning seven states (Arizona, Colorado, Idaho, Nevada, New Mexico, Utah, and

Wyoming). The ecosystems of the Southern Rockies LCC can be divided into more than a dozen distinct regions ranging from the lowland Sonoran and Mojave deserts to the highlands of the Southern Rocky Mountains, though the mountainous areas of Arizona, Colorado, New Mexico, and Utah are most widely represented (Figure 2; Omernik & Griffith, 2014). Though management priorities vary within the Southern Rockies LCC, conservation efforts within the region primarily focus on five focal resources: cultural resources, mule deer and elk, native fish, streamflow, and sagebrush-steppe ecosystems.

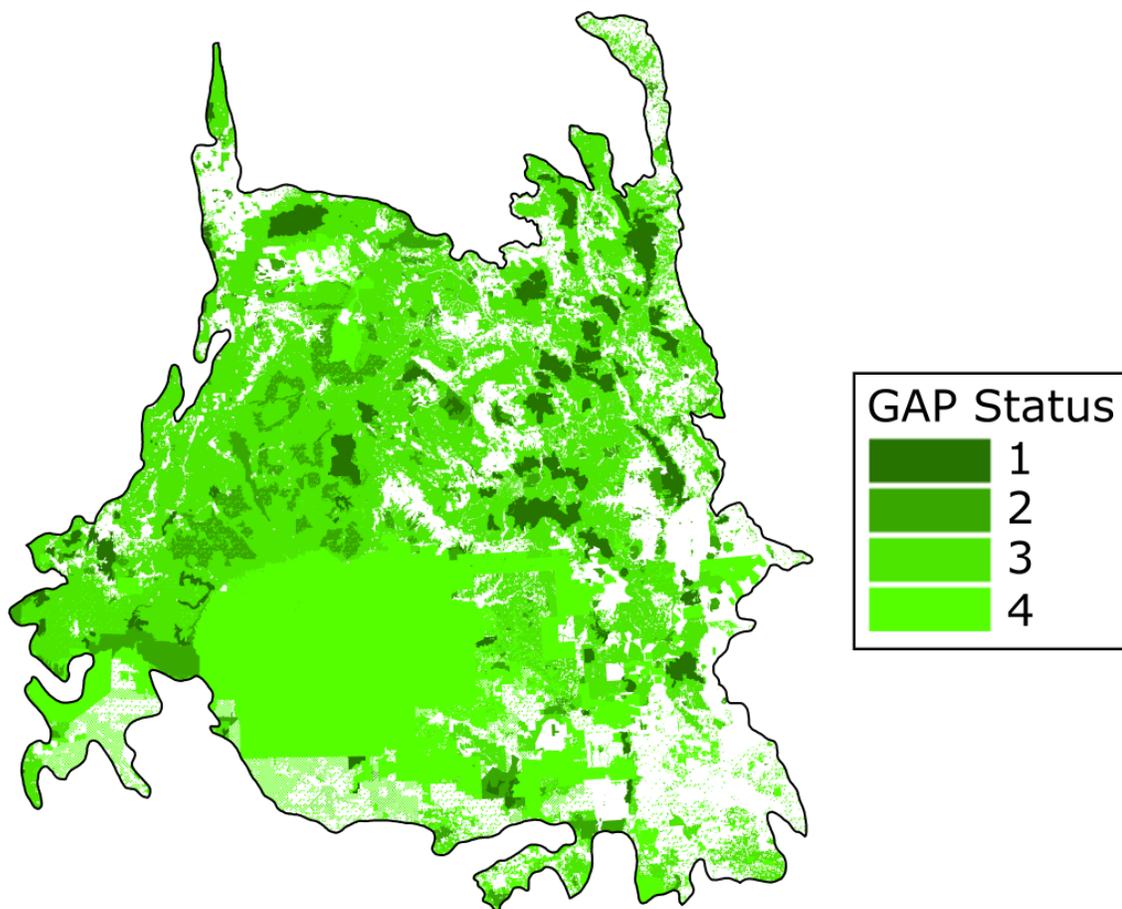
With 81.7105% of its extent listed within the USGS Protected Areas Database of the United States (PADUS), the Southern Rockies region already receives widespread landscape management. However, these areas receive different levels of protection, allowing for varying degrees of management intensity, changes to ecological disturbance regimes, and extractive uses (Figure 3). Of the PADUS areas, generally only those designated with a GAP Status of 1 or 2 meet the global definition of a protected area by the International Union for Conservation of Nature (IUCN). While these protected areas (GAP Status 1 or 2) cover more than 67,000 square kilometers, they account for only 11.46% of the entire Southern Rockies region (Table 1). To reduce potential edge effects when conducting certain analyses - namely the comparison of climate velocity results and the modeling of climate connectivity – this study region was broadened to include the geographic extent of a 100 kilometer buffer surrounding the Southern Rockies.



**Fig. 1** Spatial Extent of the Southern Rockies Landscape Conservation Cooperative (green) in the Western United States



**Fig. 2** EPA Level III Ecoregions of the Southern Rockies LCC



**Fig. 3** Protected areas of the Southern Rockies LCC

**Table 1** USGS protected area GAP Status definitions and their coverage within the Southern Rockies LCC

<b>GAP Status</b>	<b>Definition</b> ( <a href="https://gapanalysis.usgs.gov/blog/iucn-definitions/">https://gapanalysis.usgs.gov/blog/iucn-definitions/</a> )	<b>Area Covered</b> (km <sup>2</sup> )	<b>Percent of Region Covered</b>
<b>1</b>	“An area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a natural state within which disturbance events (of natural type, frequency, intensity, and legacy) are allowed to proceed without interference or are mimicked through management.”	29,424	5.0527
<b>2</b>	“An area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a primarily natural state, but which may receive uses or management practices that degrade the quality of existing natural communities, including suppression of natural disturbance.”	37,636	6.4629
<b>3</b>	“Area having permanent protection from conversion of natural land cover for the majority of area. Subject to extractive uses of either broad, low-intensity type (eg. Logging) or localized intense type (eg. Mining). Confers protection to federally listed endangered and threatened species throughout the area.”	267,835	45.9929
<b>4</b>	“No known public/private institutional mandates/legally recognized easements.”	140,938	24.202

CHAPTER 2  
METRICS FOR PROMOTING CLIMATE CHANGE RESILIENCE  
WITHIN THE SOUTHERN ROCKIES

**ABSTRACT**

In order for conservation to effectively adapt to climate change, it first requires a broader understanding of how climate change impacts are likely distributed. Assessing climate change risks and vulnerabilities across broad landscapes containing an array of species, communities, and ecosystems requires estimates of climate change resilience that are generally applicable across all relevant ecological features. Using broader metrics of climate change exposure and connectivity, I evaluated the areas of the Southern Rockies region based on their relative ability to enable the persistence of the region's ecological resources under a variety of projected climate shifts. Modeling climate velocities revealed high spatial heterogeneity in climate exposure within the study regions. Though velocity-based climate exposure varied depending on the bioclimatic variable used to calculate them, the general spatial distribution of exposure was relatively consistent across multiple future climate scenarios, with just the absolute value of velocity changing. Although the absolute velocity changed, relative differences in velocity among locations remained the constant, supporting the robustness of these metrics. Simulated climate connectivity corridors provided further means for assessing the variability of adaptive capacity throughout the region. With careful consideration of the assumptions of each, these proxy metrics of climate change resilience demonstrate high potential for aiding in conservation decision-making that spans multiple systems.

## INTRODUCTION

Protecting multiple ecological resources from the dynamic impacts of climate change requires conservation measures that promote the ability of those resources to adapt to shifting climate across the landscape (Hannah *et al.*, 2002b; Lawler, 2009; Hannah, 2011). When seeking to quantify that adaptability, one must first understand the distributions of climatic change impacts that influence vulnerabilities. Within this context, vulnerability is typically defined as a function of exposure to climate shifts, sensitivity to those shifts, and adaptive capacity (Dawson *et al.*, 2011). Many climate-adaptive strategies proposed and implemented in conservation are based on adequately assessing the vulnerability of specific conservation targets, from individual taxa to broad ecosystem types (Settele *et al.*, 2014). When it comes to the protection of sensitive species (a commonly sought after objective in conservation), climate vulnerability has been assessed using an assortment of correlative, mechanistic, and trait-based approaches (Pacifi *et al.*, 2015). Of these approaches, those dealing with the modeling of past and future species distribution shifts and climate change refugia – areas where species are less vulnerable to climate shifts – have been the most extensively studied (Schloss *et al.*, 2012; Settele *et al.*, 2014; Hannah *et al.*, 2016; Jones *et al.*, 2016; Morelli *et al.*, 2016). However, understanding the climatic vulnerabilities of each individual species or ecosystem is time consuming and costly, typically making it difficult to apply this approach across broad landscapes (Schloss *et al.*, 2012). In order to more rapidly begin to account for the pressures of climate change in the landscape conservation process, it may be more prudent to focus on understanding less system-dependent differences in climatic change exposure and adaptive capacity across landscapes.

Climate velocities represent a biologically relevant method for quantifying climate change exposure in a way that is independent of the presence of specific taxa or ecosystems. Instead, climate velocity uses the distributions of pre-defined climate variables to calculate the rate at which any organism in a given area would theoretically have to travel in order to get track climate shifts (Loarie *et al.*, 2009). Fundamentally, these velocities can be quantified simply using spatial and temporal gradients in climate conditions (Loarie *et al.*, 2009; Burrows *et al.*, 2011, 2014; Dobrowski *et al.*, 2013). For additional ecological relevance, climate velocities can be also assessed on the basis of future climate analogs, land units that are expected to have future climate conditions that match with the conditions of areas within the present landscape (Carroll *et al.*, 2015; Hamann *et al.*, 2015). Across an entire landscape of gridded climate cells, analog-based climate velocity is calculated by taking each individual cell, pairing it with the nearest cell projected to have matching climate in the future, and then dividing the geographic distance between those two cells by the time difference between present and future time periods (Hamann *et al.*, 2015).

In order to broadly reduce climate change vulnerabilities, one should also promote connectivity, the ability of organisms to move across the landscape (Lawler, 2009; Hannah, 2011). When evaluating landscape connectivity within the context of enabling multiple species to shift their ranges in response to climate change impacts, it is often recommended that protected corridors between core areas follow climatic gradients (Beier, 2012; Nuñez *et al.*, 2013). While landscape connectivity models based on individual target species ranges and movement patterns can provide targeted insight into the ability of that species to move within current landscapes, the mapping of climate-

based connectivity can further aid in identifying areas critical for reducing climatic vulnerabilities, particularly where climate conditions are very different between core areas (Beier, 2012). Given the careful parameterization of the models of climate connectivity, the corridors resulting from such models can provide a greater understanding of where capacity for adapting to climate change can be most effectively enhanced.

Despite the oft-stated importance of accounting for climate exposure and connectivity in landscape conservation and management, the processes for evaluating these multiple metrics associated with climate change resilience have not been widely implemented in an integrative manner that can be applied toward broad conservation decision-making. Here I specifically assess the landscape condition of the Southern Rockies region based on climate velocities and on climate gradient connectivity between major protected areas. To incorporate climate change uncertainties into my assessments, I repeated my analyses across multiple projected climate conditions, including two representative concentration pathways (RCP 4.5 and 8.5) and two time future time periods from the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the 5th IPCC Assessment Report (IPCC, 2014). By comparing relative patterns of climate exposure and connectivity across an array of modeling parameters, I was further able to evaluate the robustness of the simulation models that I utilized.

## **METHODS**

### *Climate Data*

Spatial data depicting the current and projected climate conditions across North America were obtained online from the climate database of the AdaptWest Project (Wang

*et al.*, 2016). All of these climate datasets were developed using the ClimateNA software package, which uses an approach based on localized elevation adjustments to downscale broad-scale past, present, and future climate datasets to a finer (1 km) resolution at multiple timescales. In addition to providing downscaled, monthly point-estimates for both temperature and precipitation, the software produces a set of 27 derived climatic variables of potential biological relevance, including chilling degree days, growing degree days, and mean temperature of the warmest month. I primarily used two of these bioclimatic variables – mean annual temperature (MAT) and mean annual precipitation (MAP) – in my subsequent analyses. These two metrics were chosen to broadly characterize climate conditions due to their close spatial correlation with other related variables of ecological significance within North America, including summer temperatures (Jones & Kelly, 1983; Koenig, 2002).

To reduce potential uncertainties associated with the use of climate predictions for conservation management applications, my analyses of climate exposure and connectivity were repeated under a range of scenarios that incorporate four climate projections. Current climate conditions represent average recorded values from a 1981-2010 reference climate period. Future climate data was obtained for two time periods: 2041-2070 and 2071-2100 (hereafter referred to as 2050s and 2080s, respectively). All future climate projections are based on an average ensemble of 15 general circulation models (GCMs) – CanESM2, ACCESS1.0, IPSL-CM5A-MR, MIROC5, MPI-ESM-LR, CCSM4, HadGEM2-ES, CNRM-CM5, CSIRO Mk 3.6, GFDL-CM3, INM-CM4, MRI-CGCM3, MIROC-ESM, CESM1-CAM5, GISS-E2R – included in the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the 5th IPCC Assessment Report (IPCC,

2014; Wang *et al.*, 2016). This model ensemble was built from climate projections under two distinct representative concentration pathways: RCP 4.5 and RCP 8.5. Whereas the scenario under RCP 4.5 is characterized by a stabilization of radiative forcing and represents a “middle-of-the-road” case for changing climate, RCP 8.5 corresponds to a scenario where climate conditions are the result of continued acceleration of greenhouse gas emissions in the absence of an effective climate change policy, and is often referred to as “business as usual” (Riahi *et al.*, 2011; Thomson *et al.*, 2011).

### *Climate Exposure*

To demonstrate the process of evaluating landscape components based on their relative climate exposure, I calculated analog-based climate velocities for all of North America. In order to compare changes in exposure of different climate variables, I calculated climate velocities using mean annual temperature and mean annual precipitation – both individually and in combination. All calculations and analyses were conducted using R Version 3.3.2 (R Core Team, 2016) and ESRI ArcGIS. R-code used for the calculation of climate velocities was adapted from R script algorithms provided by Hamann *et al.* (2015) as part of the AdaptWest Project (Hamann *et al.*, 2015). This analog-based method of calculating climate velocity requires that the user set a threshold value for each climate variable, a threshold that determines how similar the climate values of current and future areas must be in order to be considered analogs of one another (e.g. within 0.5°C). A smaller climate threshold indicates an increased precision for a particular climate metric, and will tend to increase the distance that organisms would need to travel in order to reach a future analog climate, resulting in greater climate velocities (Hamann *et al.*, 2015).

To investigate the relationship between climate threshold and the distance between analogs, and thus determine an appropriate threshold both for mean annual temperature and for mean annual precipitation, I repeated forward velocity calculations under a range of threshold values within a single climate projection (2080s RCP 4.5). The sensitivity of temperature-based velocity was tested using 12 thresholds between  $\pm 0.025^{\circ}\text{C}$  and  $1^{\circ}\text{C}$  and tests for the sensitivity of precipitation-based velocity were conducted using 10 thresholds between  $\pm 1$  mm and 50 mm. From the results of this sensitivity analysis, I selected a single threshold for each climate variable that was used to obtain all remaining velocity results.

For each of mean annual temperature, mean annual precipitation, and the multivariate combination of the two, I produced forward climate velocity raster datasets for all of North America under all four combined climate projections (2050s RCP 4.5, 2050s RCP 8.5, 2080s RCP 4.5, and 2080s RCP 8.5) and compared their spatial distributions. I then clipped every continental dataset down to the buffered extent of the Southern Rockies and its immediate surroundings. All areas for which climate velocity values could not be calculated – i.e. pixels with “no analog” climate – were reassigned values equal to the maximum velocity within the clipped spatial extent. Similarities in the patterns of velocity-based climate exposure estimates were quantitatively compared by looking at the spatial concordance between values, using the following process. First, I subset each of the two maps of climate velocity being compared into 10 rasters based on the quantiles of their individual values. Then, working one quantile at a time (10%, 20%, etc.), I overlaid each pair of split rasters and calculated the total number and percentage of overlapping pixels. The resulting overlap between paired quantiles was then used to

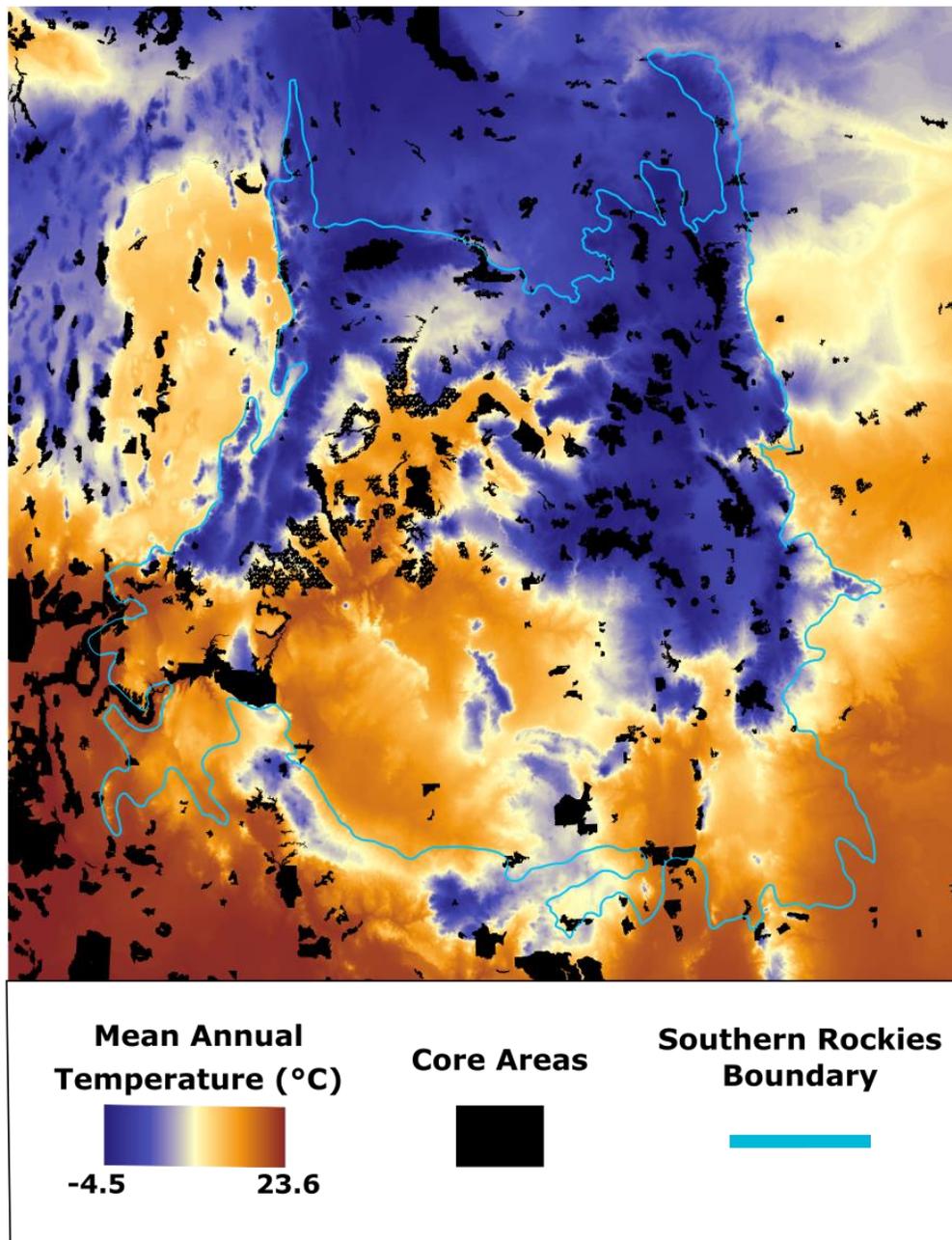
represent the spatial agreement between the two maps. This process was repeated to make three pairwise comparisons between velocity maps based on contrasting climate metrics (temperature, precipitation, multivariate), eighteen comparisons of velocity under the four climate projection (six for each climate metric).

### *Climate Connectivity*

Using mean annual temperature as a broad representation of other biologically meaningful climatic variables, I modeled climate gradient corridors networks between contiguous protected areas around the Southern Rockies. To map values of temperature-based resistance to movement between protect areas, I utilized Climate Linkage Mapper, a software tool that is part of the Linkage Mapper Toolkit for ArcGIS (McRae & Kavanagh, 2011; Kavanagh *et al.*, 2012; Nuñez *et al.*, 2013). For these analyses, I chose to simulate connectivity between all GAP Status 1 & 2 protected areas with an aggregated area of over 25 km<sup>2</sup> within the geographic extent of a 100 kilometer buffer surrounding the Southern Rockies region (Figure 4; U.S. Geological Survey Gap Analysis Program (GAP), 2016). I then directed Climate Linkage Mapper to generate raster surfaces of anisotropic movement costs based on an input raster of current (1981-2010) mean annual temperature (Wang *et al.*, 2016). I initially linked all core areas at a Euclidean distance of between 2 and 200 kilometers from one another with a difference in average temperature of greater than 0.5°C. Rasters of cost-weighted distance (CWD) for each link were computed based on temperature-based movement costs and Euclidean distances. Linkages were subsequently removed so that each core area was only linked to its nearest four neighboring core areas, by Euclidean distance. The CWD maps for each remaining linkage were then mosaicked by Linkage Mapper into a single CWD map

representing the temperature-based cost-of-movement. Areas with low movement cost were then interpreted as having high value as climate gradient corridors (i.e. high connectivity), while areas with high movement costs corresponded to low connectivity.

To evaluate the potential effect of climate shifts on connectivity between existing protected areas in the Southern Rockies, I additionally modeled corridors and flow under two projected future distributions of mean annual temperature (2050s RCP 4.5 and RCP 8.5), which I then compared to current corridors. Overall differences in model outputs (resistance values) under each climate projection were used to infer potential changes in climate connectivity under alternative future conditions. Projected increases in an area's resistance values corresponded to decreases in the value of that area as a climate corridor.



**Fig. 4** Modeling domain and inputs for climate connectivity mapping

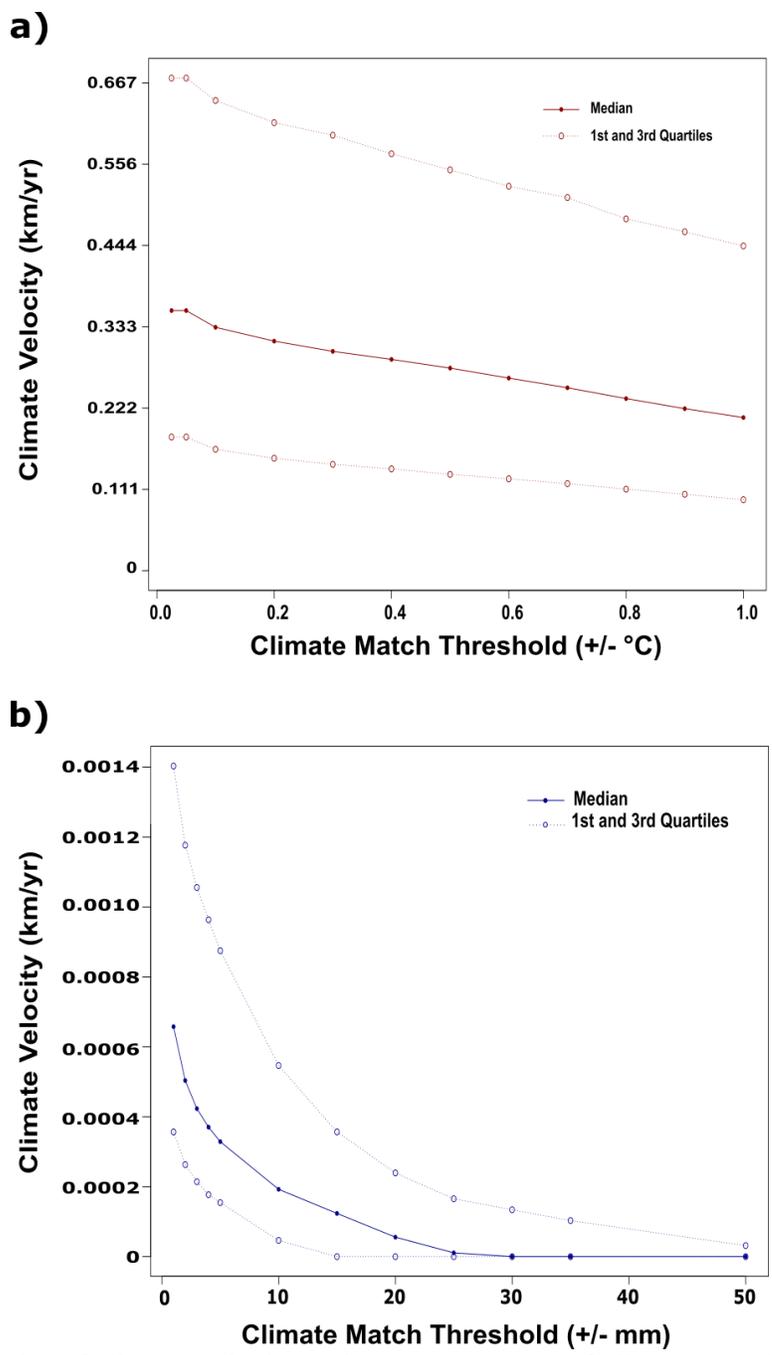
## RESULTS

### *Climate Exposure*

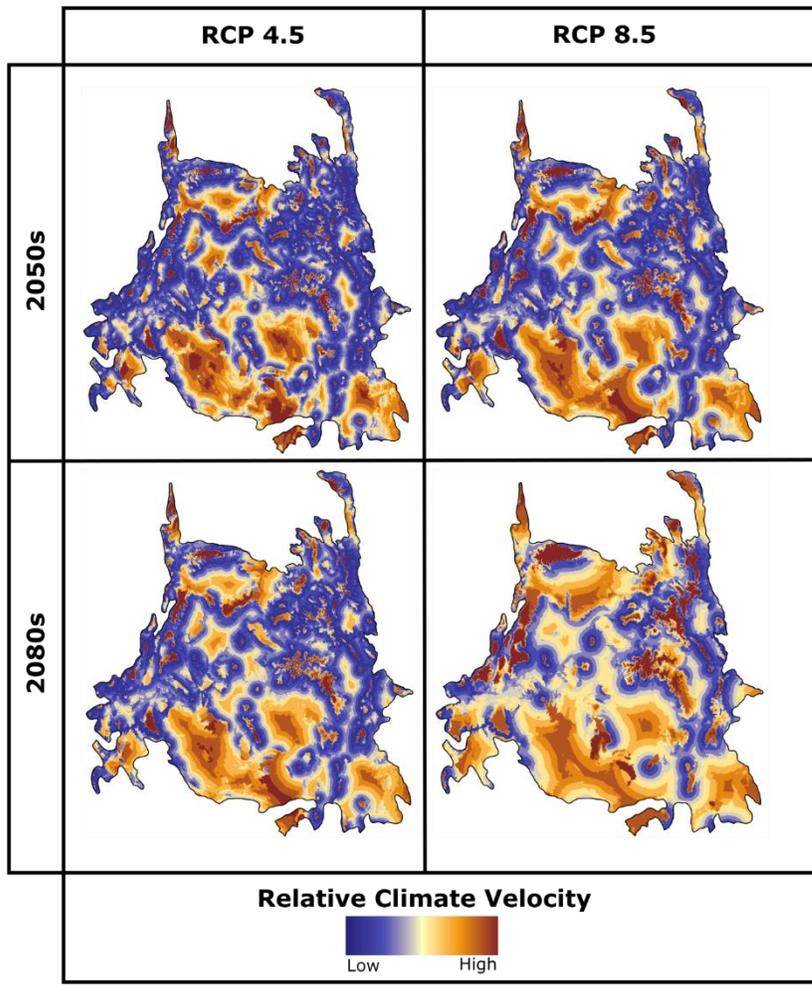
Forward climate velocity values modeled under a range of climate-match thresholds for the 2080s RCP 4.5 climate projection revealed that velocities within the buffered extent of the Southern Rockies study region respond in a relatively linear fashion at large thresholds, with more rapid increases at small values (Figure 5). Tests of temperature-based climate velocity showed that velocities within the study region increase linearly as temperature threshold was reduced, with a slight inflection point at around  $0.2\text{ }^{\circ}\text{C}$  (Figure 5a). Tests of the sensitivity of precipitation-based velocity were conducted using 10 thresholds between  $\pm 1\text{ mm}$  and  $50\text{ mm}$ . Unlike the relatively linear relationship between temperature and distance-to-match, as the precipitation threshold was decreased, velocities increased exponentially (Figure 5b). Based on these analyses, I chose to use  $\pm 0.2\text{ }^{\circ}\text{C}$  for mean annual temperature and  $\pm 5\text{ mm}$  for mean annual precipitation in all subsequent univariate and multivariate velocity calculations, while also aiming to determine the possible effects of these thresholds during later assessments of relative exposure and priority.

When used in isolation, mean annual temperature generated climate velocities that varied considerably over the study region, but demonstrated similar spatial patterns in exposure under all four climate projections (Figure 6). This spatial variation across the study area suggests that certain areas will always be relatively severely impacted, while others will be relatively lightly impacted by future changes in mean annual temperature. The lowest absolute climate velocities based on mean annual temperature were seen using the 2080s RCP 4.5 projection (mean =  $0.0054$ , SD =  $0.0063$ ), while the highest are

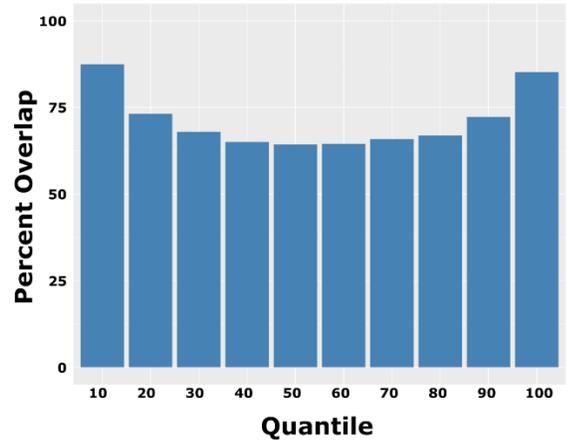
observed in the 2050s RCP 8.5 projection (mean = 0.0131, SD = 0.0157). While velocities under all four projections demonstrated a high degree of similarity in their patterns – measured using percent overlap between 10<sup>th</sup> quantiles – considerable differences were observable (Figure 7). In particular, the velocity results of the 2080 RCP 8.5 projection showed the least pattern similarity to other climate projections, especially with the 2050 RCP 4.5 (mean quantile overlap = 19.67%). Quantile overlap was greatest between the 2050 RCP 8.5 and 2080 RCP 4.5 projections (mean = 71.28%). However, the areas with the highest and lowest climate velocity (top and bottom quantiles) appear to have retained the highest amount of spatial overlap (Figure 7). Therefore, although these sensitivity analyses comparing across climate projections shows some quantitative differences in velocities, the relative exposure and importance of different areas remains consistent.



**Fig. 5** Sensitivity of climate velocity estimates to a range of climate match thresholds, based on a) mean annual temperature and b) mean annual precipitation



**Fig. 6** Relative forward climate velocities in the Southern Rockies under four climate projections, calculated using changes in mean annual temperature alone

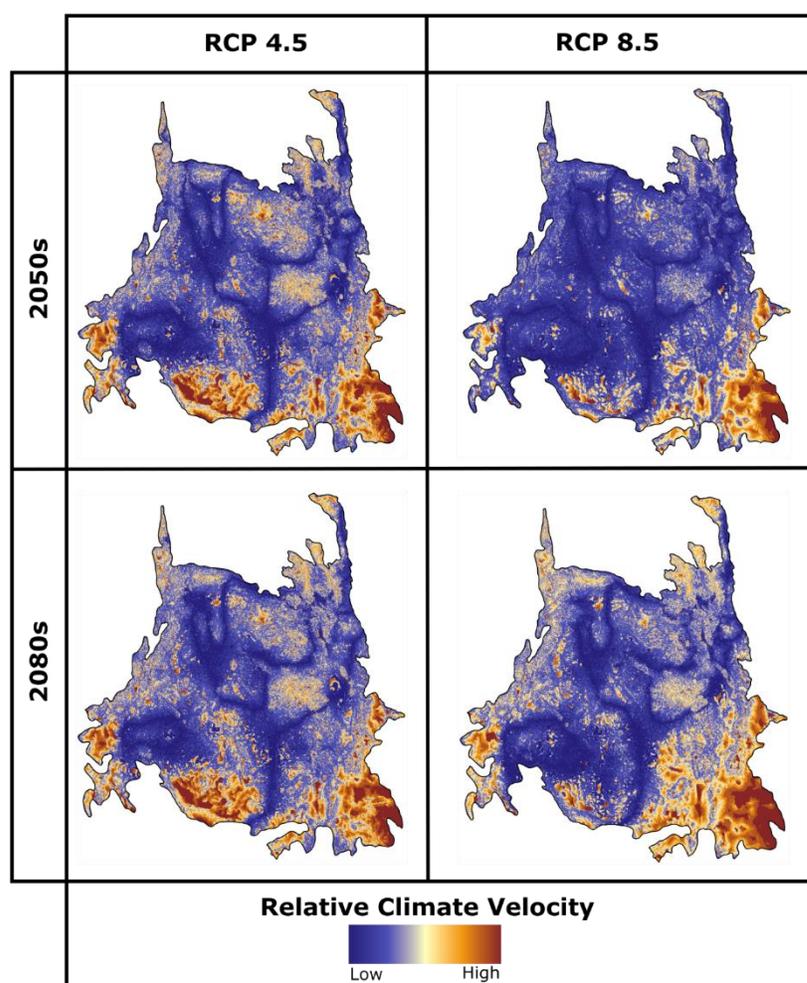


**Fig. 7** Quantile pattern comparison between the two most similar maps of climate velocity based on mean annual temperature (2050s RCP 8.5 and 2080s RCP 4.5)

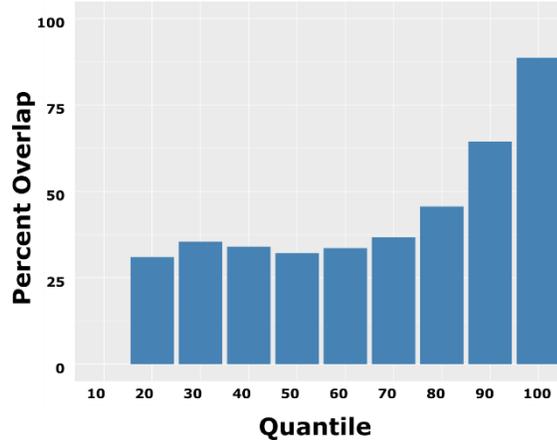
When mean annual precipitation was used in isolation (i.e. mean annual temperature not included) climate velocities again varied considerably across the spatial extent (Figure 8). Across the four different climate predictions, the absolute climate velocities once again varied in magnitude, but demonstrated similar spatial patterns of exposure (Figure 9). The lowest absolute climate velocities based on mean annual precipitation were seen using the 2080s RCP 4.5 projection (mean = 0.0009, SD = 0.0018), while the highest are observed in the 2050s RCP 8.5 projection (mean = 0.0039, SD = 0.0043). Pattern similarity was greatest between the 2050 RCP 4.5 and 2080 RCP 4.5 projections (mean = 44.64%; Figure 9). For all six pairwise pattern comparisons, the lowest quantile of precipitation velocities always showed zero overlap, though the highest quantile exhibited high overlap across pairs. As the relative patterns across the four climate predictions remained the comparable for both mean annual temperature and mean annual precipitation (although absolute values changed), I therefore focused on one particular climate projection (2080s RCP 4.5) to compare spatial differences in climate velocities based on mean annual temperature, mean annual precipitation, and both metrics in combination.

Comparing within each climate projection, absolute climate exposure varied considerably depending on which climate metric or metrics were used to derive climate velocity (Figure 10). Under the 2080s RCP 4.5 climate projection, overall velocities within the extent of the study region were lowest when based on mean annual precipitation (mean = 0.0009 km/year, SD = 0.0018), moderate when based on mean annual temperature (mean = 0.0054 km/year, SD = 0.0064), and highest when based on the combination of both temperature and precipitation (mean = 0.0343 km/year, SD =

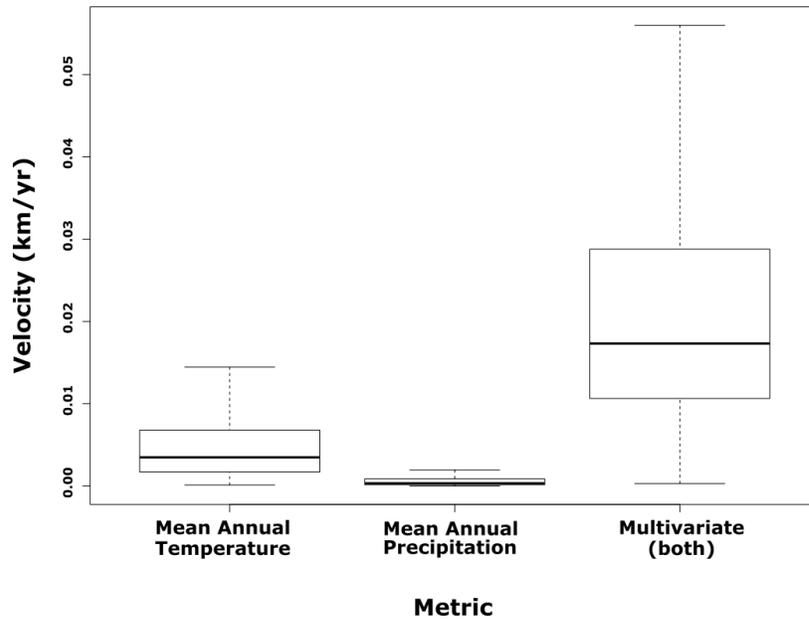
0.0716). Across the entire study region, climate velocities were generally greater when derived from two metrics simultaneously than when either of the metrics were treated in isolation. This was to be expected given that the criteria for two areas being climate analogs have been greatly narrowed, since they are now being dictated by two climate parameters whose relative velocities have very distinct spatial patterns (Figures 11a and 11b).



**Fig. 8** Relative forward climate velocities in the Southern Rockies under four climate projections, calculated using changes in mean annual precipitation alone

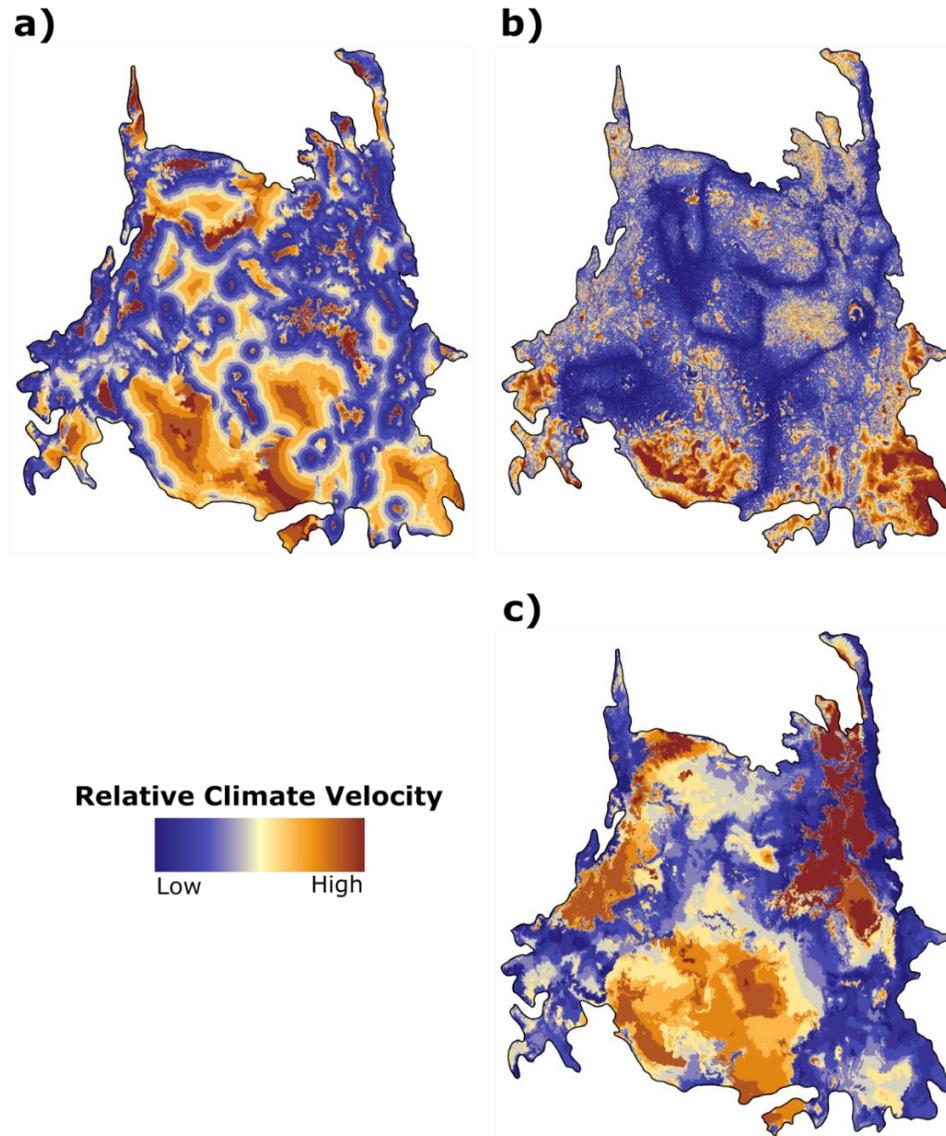


**Fig. 9** Quantile pattern comparison between the two most similar maps of climate velocity based on mean annual precipitation (2050s RCP 4.5 and 2080s RCP 4.5). Note that there was no observed overlap in the lowest quantile

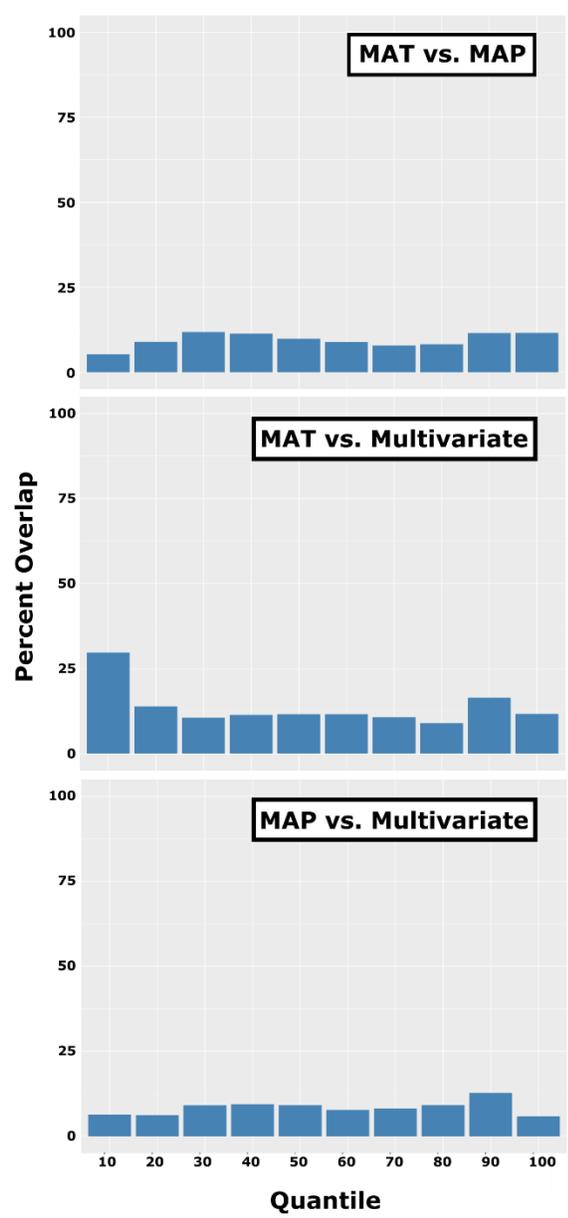


**Fig. 10** Mean climate velocities for the Southern Rockies calculated using different climate metrics

When climate velocities were based on climate analogs of both mean annual temperature and mean annual precipitation together, the spatial distribution of climate velocities was substantially different than that observed when treating either metric in isolation (Figure 11c). When both climate metrics used simultaneously in calculating velocities, the patterns of exposure are seemingly composed of a combination of the high velocity areas seen when each of the individual metrics are used. For example, in Figure 11c, the high climate velocities observed for the Uinta Mountains and the Colorado Rockies appear to correspond with the high velocity areas seen in Figure 11a, while the high velocities seen in the southern parts of the region also line up with those in Figure 11b. However, pattern similarity between velocity maps was generally low, with the greatest being between temperature-based velocity and the multivariate velocity (mean quantile overlap = 13.66%; Figure 12). Similarity was even lower between temperature velocity and precipitation velocity (mean = 9.56%) and between precipitation velocity and multivariate velocity (mean = 8.40%). This would suggest that differences in mean annual temperature drive the patterns of multivariate velocity more strongly than differences in mean annual precipitation. Generally, the differences in the distribution of high and low velocity areas observed among the three maps indicate the potential importance of guiding climate-related management decisions using the variable or variables that are most appropriate for one's particular question.



**Fig. 11** Analog-based climate velocities based on a) mean annual temperature, b) mean annual precipitation, and c) a multiplicative combination of both climate metrics. Climate velocities shown here were generated using the 2080s RCP 4.5 climate projection, a temperature threshold of  $\pm 0.2^{\circ}\text{C}$  and a precipitation threshold of  $\pm 5$  mm

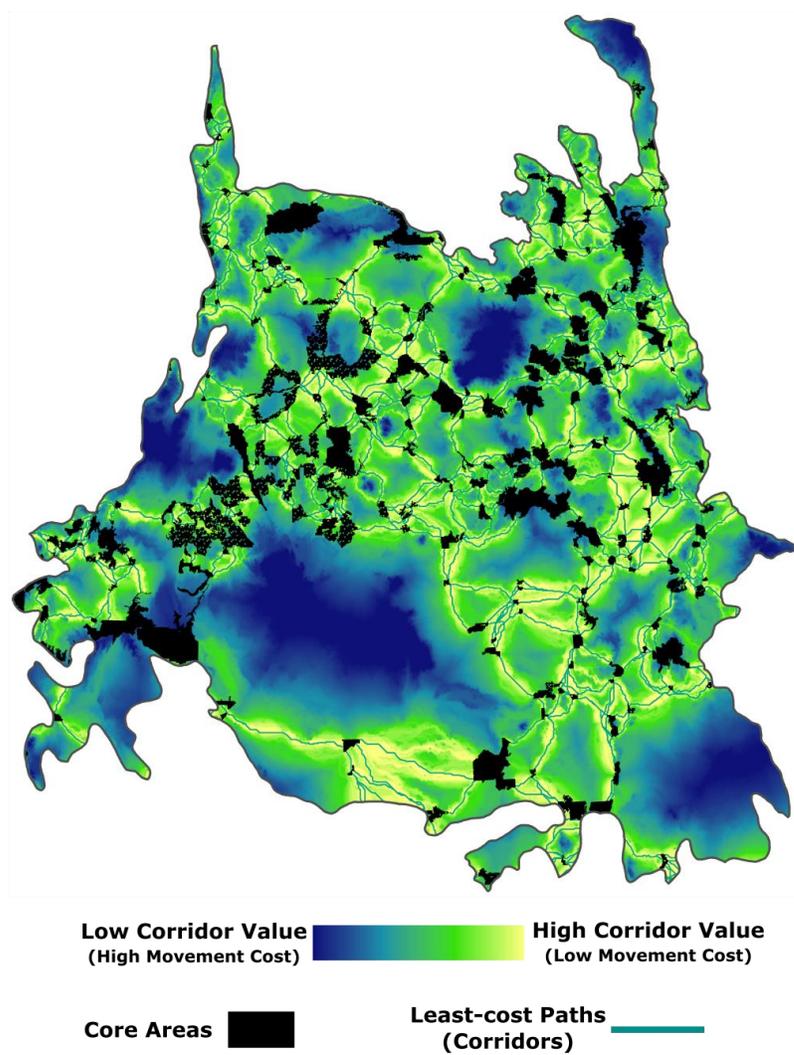


**Fig. 12** Similarity between climate velocity patterns generated using contrasting metrics a) temperature vs. precipitation, b) temperature vs. multivariate, and c) precipitation vs. multivariate

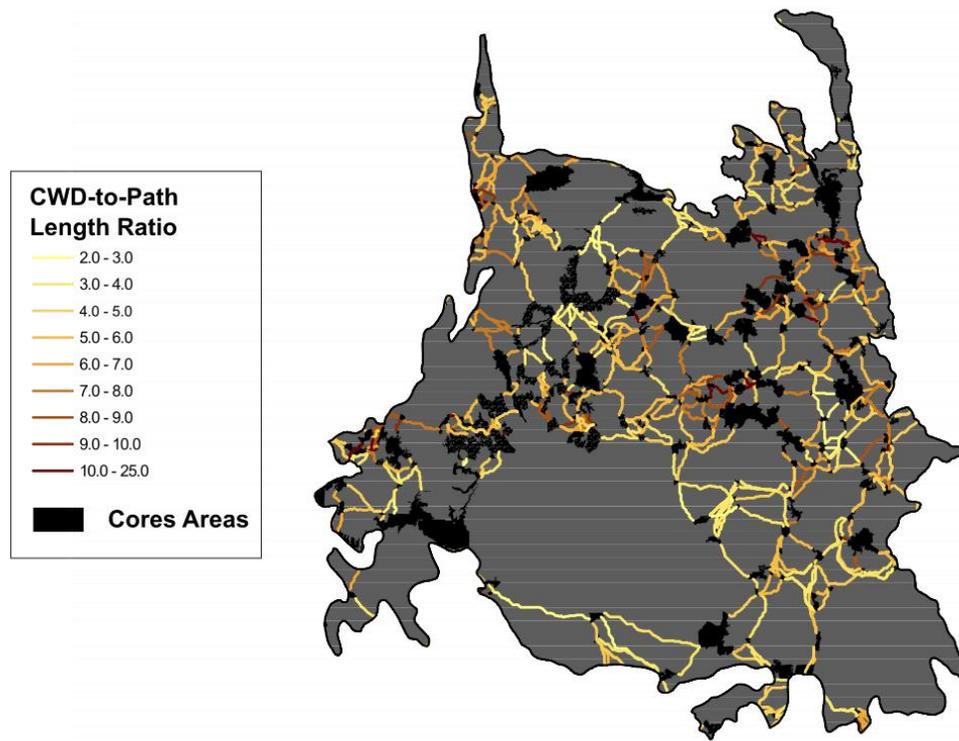
### *Climate Connectivity*

I modeled climate connectivity between all large (>25 km<sup>2</sup>) protected areas within and immediately surrounding the Southern Rockies using present and future gradients in mean annual temperature (Figure 13). Under all three model scenarios, a total of 1,188 least-cost path corridors were generated, connecting 467 core protected areas to their nearest four neighboring core areas. Within study region itself, 230 core areas were linked to their nearest neighbors via 598 individual climate gradient corridors. Present corridors varied considerably in their inefficiency at reducing climate-based movement costs, as represented their individual ratios of cost-weighted distance to path length (mean = 5.531, SD = 2.320; Figure 14). Least-cost corridors with higher ratios generally corresponded to paths that spanned steeper temperature gradients over their entire length.

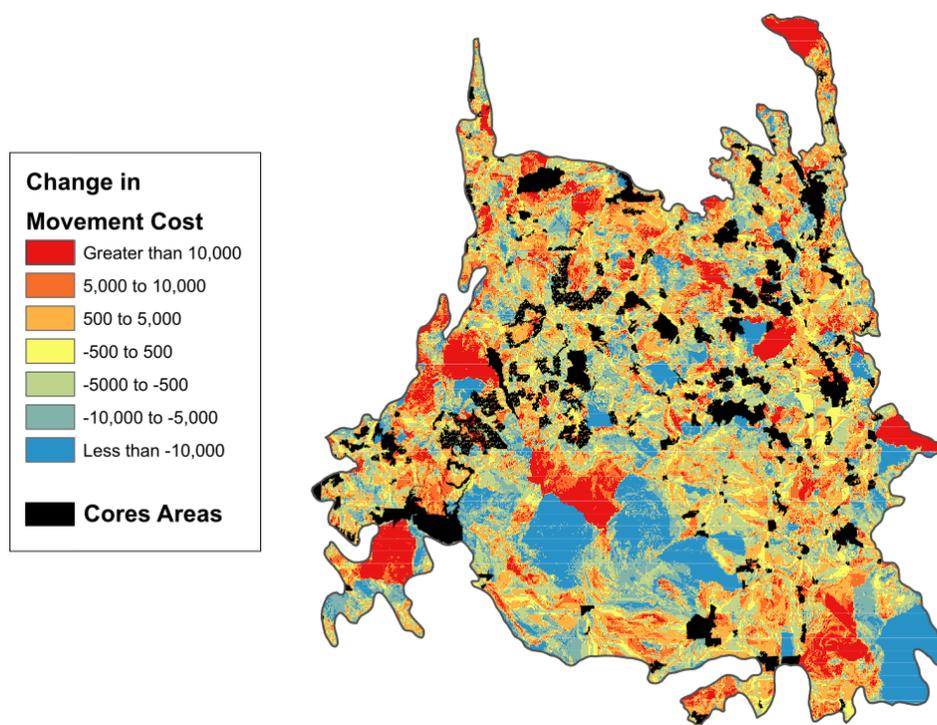
Overall differences in movement costs between present and projected climate corridors revealed both the stability of corridor locations and sensitivity of climate models to the dynamic shifts. Certain areas, particularly those with high corridor values under both present and projected models, demonstrated the largest overall increases and decreases in cost-of-movement (Figure 15). In other areas – including the locations of many least-cost-path corridors – connectivity remained relatively constant, representing climate corridors that are more robust under future climate. Proportional changes (future over present) in climate corridor values reveal that temporal shifts in connectivity primarily occur where individual climate corridors individual climate corridors in the present are replaced by low connectivity areas in the future (Figure 16). Connectivity values remained relatively unchanged or increased across much of the study region.



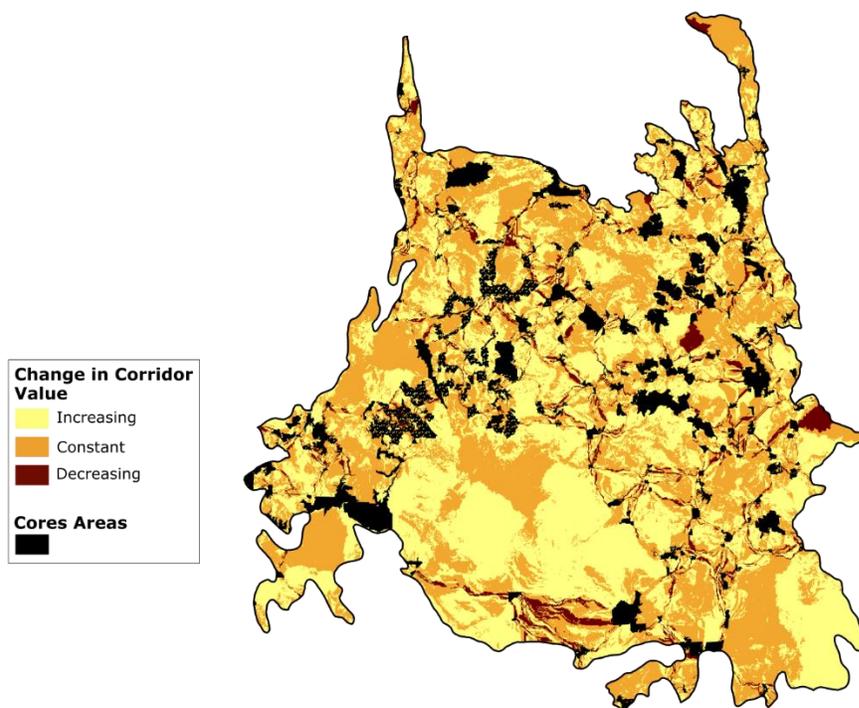
**Fig. 13** Modeled climate corridors under present climate conditions



**Fig. 14** Least-cost paths (corridors) by efficiency, represented using the ratio between cost-weighted distance (CWD) and the Euclidean distance of the path



**Fig. 15** Overall in climate-based movement costs between present and projected future conditions (2050 RCP 4.5). Red areas correspond to large increases in costs (decreases in corridor value), whereas blue corresponds to decreases in costs (increases in corridor value)



**Fig. 16** Proportional changes in climate connectivity between present and projected future conditions (2050 RCP 4.5)

## DISCUSSION

Within natural systems experiencing persistent and highly variable environmental impacts related to shifting climate conditions, promoting the broad adaptability and resilience of regional biodiversity requires wide assessments of vital landscape characteristics, including climate exposure and connectivity. Through my assessments of climate exposure and connectivity with the Southern Rockies region, I evaluated the spatial and temporal heterogeneity of broad ecological vulnerabilities that could be used to drive climate-adaptive conservation decisions. First, I quantified spatial patterns in terrestrial climate exposure using analog-based climate velocities under a range of model parameters and climate projections. I then assessed climate connectivity based on gradients of mean annual temperature and found substantial differences in climate corridors modeled under present and future conditions. While these modeled results

demonstrated sensitivity to certain inputs – especially climate variables – they were also validated through their robustness across multiple uncertain climate projections.

When making conservation decisions based on any sort of broad landscape-scale analyses such as these, it is critical to remain mindful of the fundamental assumptions of one's methodological approaches. For one, assessments of climate exposure and connectivity based on climate predictions depend on the use of only a select few climate variables – such as mean annual temperature and precipitation – that are assumed to be the closest approximations of many other more biologically-meaningful variables. Since it can be readily demonstrated that patterns in climate shifts and their impacts vary depending on which aspect of climate is being looked at, practitioners of landscape climate assessment and conservation prioritization must be careful about which climate variables they select. On this note, one must keep in mind that certain climate variables, particularly temperature-based variables, have much lower uncertainty due to the greater degree of agreement between the predictions of global and regional climate models of temperature, relative to those for precipitation (Hawkins & Sutton, 2009; Flato *et al.*, 2013). This suggests that temperature variables would be more reliable as a basis for management actions. Secondly, conducting analyses at broad spatial resolutions of 1 km<sup>2</sup> and larger ignores much of the finer scale variation in climate vulnerability. Through the use of coarser spatial resolutions, one cannot determine the presence or absence of small-scale climate microrefugia, though large-scale macrorefugia can still be identified (Ashcroft, 2010). Thirdly, it is important to note the considerable differences between the four climate projections that were used to calculate climate velocity and connectivity. Vulnerability assessments utilizing climate model projections over longer time periods

(e.g. the 2080s) are inherently less certain than those for shorter time periods (e.g. the 2050s) and do not align as well with shorter time-scales of ecology and human decision making (Chapman *et al.*, 2014). Additionally, there is considerable uncertainty of human behavior in the trajectories that will lead to the contrasting emissions scenarios (RCP 4.5 vs. RCP 8.5). However, validating exposure and connectivity models under multiple climate projections has served to evaluate the robustness of these models to uncertain future conditions. These assumptions, among many others, highlight some areas of caution that must be carefully considered by managers when making decisions about where best to undergo new conservation actions.

Despite the caveats associated with the use of generalized landscape approaches for guiding conservation making, they provide important information that can be helpful for natural systems managers looking to prepare their systems for the ongoing impacts of rapid climate change. Across Utah, the Intermountain West, and regions around the world, biological systems are expected to respond to climate change over vast spatial scales. In order to conserve the diversity of those systems, greater efforts must be made to explicitly incorporate the distribution of climate change impacts into conservation efforts. Moving forward, I believe that the use of systematic landscape planning strategies based on climate vulnerability and connectivity will provide an efficient method for prioritizing conservation actions in a manner that is directly applicable to aiding real-world management efforts to tackle the impacts of climate change.

CHAPTER 3  
SYSTEMATICALLY INCORPORATING CLIMATE RESILIENCE METRICS INTO  
LANDSCAPE CONSERVATION

**ABSTRACT**

In the face of climate change, protected area conservation must explicitly account for variability in the vulnerability of ecological systems to multiple shifting environmental conditions. When prioritizing conservation across broad landscapes, it is often prudent to focus on areas where low levels of climate exposure (refugia) and high levels of connectivity (corridors) enhance the resilience of the overall system. While broad metrics of exposure and connectivity can alone aid in identifying priority areas, they often fail to account for the distributions of species and other ecological features necessary for meeting management goals. Frameworks for spatially prioritizing conservation to account for climate change impacts must be able to simultaneously address management goals (e.g. species protection) and the factors affecting the likelihood of achieving those goals. By integrating a wider variety of social-ecological variables, systematic landscape planning strategies can be utilized to efficiently identify priority areas for potential conservation. I estimated climate exposure and climate connectivity within the US Southern Rockies region. I then used the software Marxan to prioritize areas of minimal climate exposure and maximal connectivity, while additionally accounting for the presence of species of interest, protected areas, and environmental risks. Lastly, I evaluated the adaptability of existing protected areas by comparing their characteristics with those of optimized climate refugia. This model framework successfully identified priority climate refugia and corridors that also

contained the ranges of the region's threatened wildlife species. Explicitly accounting for the presence of human development as a risk to conservation success served to further identify the highest priority areas. While some optimized climate refugia fell within existing protected areas, the extent of the refugia aligned more closely with areas of lowest exposure. While climate exposure and modeled priority were similar between the entire protected area system and the overall region, they varied considerably within and between individual protected areas. These results highlight the need for more thorough spatial assessment of factors contributing to ecological vulnerabilities and likelihoods of conservation success. I hope that the results and framework that I outline here will aid managers in efficiently allocating conservation resources with the goal of promoting ecological resilience.

## **INTRODUCTION**

Though the establishment and management of widespread networks of protected areas remains a central strategy for the conservation of ecological resources, it is unclear how well these largely static systems will be able to bear the impacts of climate change (Game *et al.*, 2011; Ban *et al.*, 2012). With individual protected areas already experiencing unprecedented ecological shifts driven by climate change, their ability to maintain climate characteristics within their borders appears compromised (Marris, 2011). Given that many of these smaller-scale protected landscapes will continue to change, preserving biodiversity and other natural resources across wider regions necessitates enhancement of landscape characteristics that allow for species to adapt, making them more resilient to the impacts of climate (Hobbs *et al.*, 2014).

While it remains important to consider whether current protected area systems can

survive the impacts of climate change, promoting regional climate resilience requires evaluating new areas for potential conservation. Although present protected areas demonstrate clear value to conservation here and now, it is likely that that value will change in the future, and that better conservation outcomes could be produced through altering protected area networks (Fuller et al., 2010). For instance, in the process of evaluating landscape-level climate change resilience, it may be found that existing protected areas contain optimal climate refugia. However, certain other protected areas could alternatively exhibit the highest potential for being impacted by climate change, with better climate refugia falling outside their current borders. In order to maintain or even increase conservation values across broad regions, protected area systems could be adapted to incorporate areas of limited climate vulnerability, namely the climate refugia and corridors that enable organisms to seek out new, more suitable climates (Hannah, 2011).

The distributions of metrics closely associated with climate change vulnerability, such as climate exposure and connectivity, play central roles in conservation decision making processes designed to account for climate change. While numerous methods for broadly evaluating climate change vulnerability already exist, they are typically implemented on a case-by-case basis and their outputs require additional synthesis in order to make the information more usable for decision makers. In the previous chapter I demonstrated how estimations of climate velocities and connectivity can be used to broadly assess vulnerability to climate change across entire landscapes. However, these generalized metrics are notably limited in their ecological specificity in that they are primarily based on abiotic parameters of climate change. For them to effectively guide

conservation decisions, these coarse filter metrics must be subsequently combined with the biotic features that are of interest to conservation, such as threatened species (Beier, 2012). Otherwise, any landscape conservation efforts driven purely by climate impact metrics may fail to meet conservation targets for actual species and ecosystems, as evidenced by suboptimal results in the global protection of threatened species (Venter et al., 2014). Thus, methodological frameworks are required for explicitly guiding conservation based on ecological goals while also reducing climate vulnerabilities, especially when those goals conflict with one another (Reside et al., 2017).

In having to reconcile multiple overlapping goals and management priorities, whether climate-driven or not, conservation decisions must efficiently prioritize where conservation actions should occur in order to make effective use of limited resources. Fortunately, tools from the field of spatial prioritization – including the software package Marxan (Ball et al., 2009) - have long been utilized for this purpose of simultaneously achieving multiple conservation targets while incurring minimal costs (Wilson et al., 2006). However, as addressed in Chapter 1, efforts to spatially prioritize conservation based on climate change and its impacts have been rather limited (Jones et al., 2016). While many of these studies have dealt with spatially prioritizing based on reducing climate exposure, assessing climate refugia, and protecting diverse ecological landscapes (Game *et al.*, 2011; Ban *et al.*, 2012; Levy & Ban, 2013; Carroll *et al.*, 2017), significant research gaps are evident. Notably, few studies have either incorporated multiple conservation objectives or explicitly accounted for a multitude of stressors and risks associated with climate change (Jones *et al.*, 2016). There is an apparent need for conservation decision frameworks that can integrate climate-related impacts with

contrasting management objectives across different systems.

In addition to explicitly and efficiently accounting for multiple competing management targets, spatial prioritization for climate change must be able to account for a wider variety of social, economic, and political risks, particularly on the sub-national and regional scales at which landscape conservation planning occurs. Climate change is one factor among many influencing the ability to conserve ecological resources. In order to bridge gaps between climate-based conservation theory and practice, one must still account for the anthropogenic activities that constrain conservation success (Heller & Zavaleta, 2008). Despite this need, the direct and indirect effects associated with people and their responses to climate change have been relatively understudied, particularly when it comes to spatial prioritization (Faleiro et al., 2013; Chapman et al., 2014; Jones et al., 2016). Given the undeniable global prevalence of anthropogenic influences on biodiversity, new methods for spatially prioritizing conservation based on climate change must be able to account for the risks to conservation success, particularly associated with people (Game *et al.*, 2013).

Especially in landscapes where vulnerabilities to climate change are highly variable, strategies for systematic landscape planning can be utilized to efficiently meet multiple conservation goals in a manner that explicitly integrates those vulnerabilities with additional factors affecting conservation success. Based on the prior assessments of metrics influencing climate vulnerability (exposure and connectivity), I used the software program Marxan to systematically construct arrays of potential conservation networks aimed at enhancing climate change resilience across the Southern Rockies region. I further assessed how the characteristics of the resulting high priority conservation areas

changed according to the distributions of species, existing protected areas, and anthropogenic land cover risks. Finally, I used values of climate exposure and modeled conservation priority to quantify the ability of current protected areas to cope with climate shifts.

## **METHODS**

### *Study Area Characterization*

The goal of this project was to optimize the locations of conservation activities across the extent of the Southern Rockies Landscape Conservation Cooperative. A 3 kilometer by 3 kilometer planning unit grid was overlaid across the landscape and used to summarize all landscape characteristics within the study region. Each planning unit's current protection status was assessed using the USGS Protected Area Database of the United States (PADUS - USGS Gap Analysis Program, 2016). All planning units that had at least 50% of their area falling within a protected area (GAP Status 1 or 2) were designated as "currently protected" during all relevant Marxan analyses. Compared to the 67,060 km<sup>2</sup> of GAP Status 1 and 2 protected areas, the 7,225 currently protected planning units covered a total of 63,968 km<sup>2</sup> (95.39% of total protected area).

### *Conservation Targets*

Species of interest consisted of all terrestrial vertebrate species within the study area that are listed under the Red List of the International Union for Conservation of Nature (IUCN) as either Near Threatened, Vulnerable, Endangered, or Critically Endangered. Species distributions and seasonal ranges of all reptiles, amphibians, terrestrial mammals, and birds within the study region were obtained from the IUCN and

BirdLife International (BirdLife International and Handbook of the Birds of the World, 2016; IUCN, 2016). The final distribution dataset consisted of the 36 ranges of 31 terrestrial wildlife species of interest (Appendix A), with the greatest diversity of species located in southeastern corner of the region (Figure 17a). The amount of each species range represented within each planning unit was calculated and proportional conservation targets in all Marxan runs were then set as 20% of each species range, corresponding to a mid-range landscape intactness threshold for forest species persistence (Betts & Villard, 2009). This 20% proportion was chosen to provide a moderately strict set of conservation targets that also closely aligns with the 17% terrestrial landscape conservation objective set through the Aichi Biodiversity Targets (CBD, 2016a). The penalty for failure to meet an individual target – the *species protection factor* (SPF) in Marxan – was set to a value of 10,000 for all species.

### *Risk*

The distribution of risk to potential protected area success was estimated based on the presence of human-modified land cover types in the National Land Cover Database (Homer *et al.*, 2015). Using the Spatial Analyst toolset in ArcGIS 10.4, I calculated the total area and proportion of each NLCD classification within each planning unit. I then quantified each planning unit's overall modification intensity by aggregating the percentages of all agricultural and developed land classifications, which included pasture, hay, cultivated crops, and lands with variable intensities of development (Figure 17b). These percentage of land modification were then directly applied to Marxan as the probabilistic risk of planning unit failure, i.e. this is the percentage of the planning unit that is unlikely to be primarily used for conservation of biodiversity.

### *Vulnerability Metrics*

Metrics of climate vulnerability to be minimized in the Marxan analyses were assigned to each planning unit based on previously calculated values of velocity-based climate exposure and climate gradient connectivity (see Chapter 2). To represent areas of high vulnerability as a function of high climate exposure, I utilized climate velocity values calculated based on analogs of mean annual temperature between present (1981-2010) and future (2050s) climate projections. Though mean annual temperature is just one biologically relevant bioclimatic variable, it was chosen for similarity in its spatial pattern with other temperature-based variables, and for the relative precision of climate model predictions for temperature, relative to those for precipitation (Flato *et al.*, 2013). I additionally used modeled climate gradient corridors to evaluate each planning unit, with areas of high climate gradient resistance (i.e. low connectivity) representing areas of high vulnerability. Within each 9 km<sup>2</sup> planning unit, the mean values of climate exposure and climate resistance were calculated (Figure 17cd) and were linearly rescaled so that each metric fit a range of 0 to 100,000.

### *Spatial Analyses*

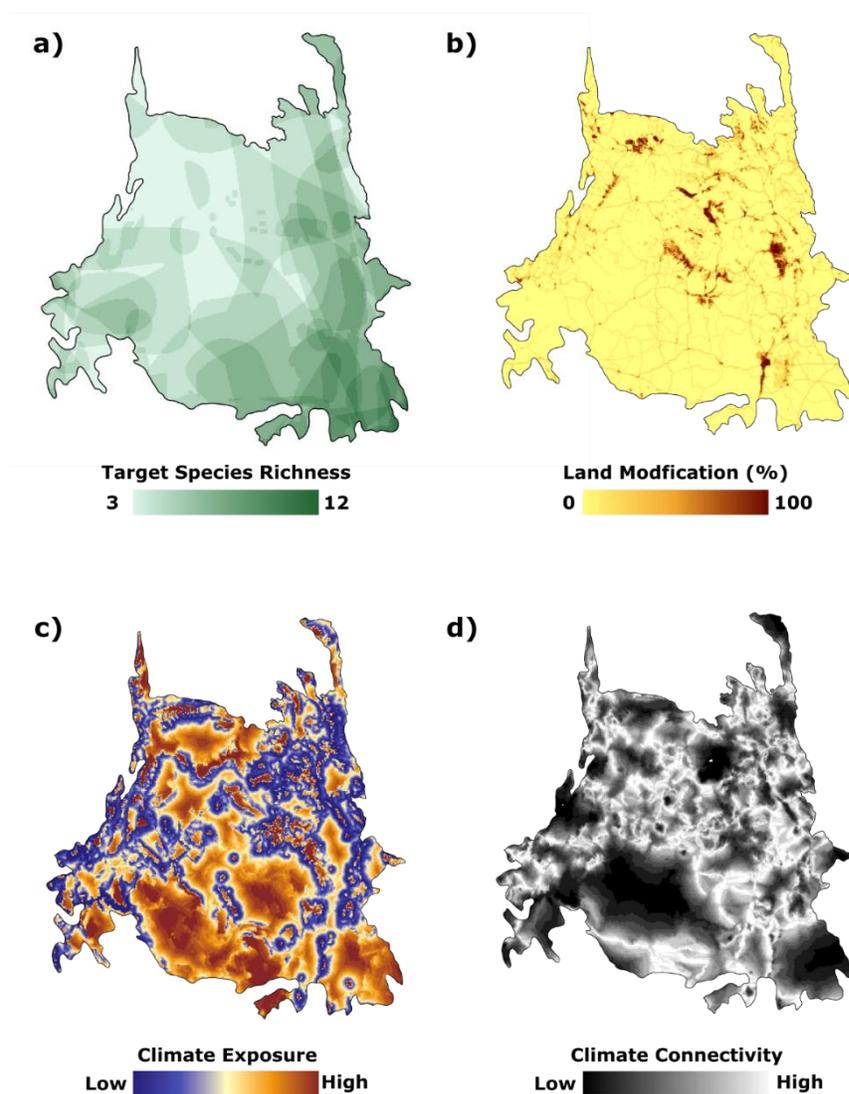
I used Marxan to systematically identify high conservation priority refugia and corridors under several potential conservation strategies for reducing climate change vulnerabilities (Table 2). For each scenario, the nearest-to-optimal (hereafter “best”) solution from 100 Marxan runs was compared with the frequency of planning unit selection all runs, in order to assess the effectiveness and efficiency of that particular conservation strategy. For each scenario, “high priority” areas were designated as the top 5% most frequently selected planning units, excluding those under current protection.

Each network of high priority areas represented approximately 30,000 km<sup>2</sup> of the study region. Under the first scenario, Marxan's objectives were to construct potential reserve networks with minimal climate exposure across the landscape while also achieving representation of all species targets. This scenario therefore identifies climate refugia that also house species of interest. In the second scenario, Marxan was instead directed to maximize the climate connectivity, resulting in the selection of climate corridors. For Scenarios 1 and 2, planning units currently under protection (>50% GAP Status 1 or 2) were automatically selected and the risks to conservation posed by land modification were not accounted for.

The parameters for the next two management scenarios were the same as those of the first two, except that the risk of planning unit failure due to existing land cover was accounted for in the selection process. The effects of including risk were quantified by comparing selection frequencies and per-planning unit exposure and connectivity in Scenarios 1 and 2 with those in Scenarios 3 and 4. Changes in selection frequency between Scenarios 1 and 3 and between 2 and 4 directly corresponded to shifts in priority that result from risk accounting. Increases in planning unit exposure and decreases in connectivity represented the ecological cost of accounting for risk.

In order to identify the optimum network of climate refugia given the stated conservation targets, Scenario 3 for minimizing climate exposure while accounting for risk was repeated without the automatic inclusion of planning units currently under protection. Similarity in the patterns of priority resulting from Scenarios 3 and 5 was evaluated as the spatial concordance between the high priority areas identified under those two scenarios. Finally, to quantify the effectiveness of existing protected areas as

climate refugia, I compared the cumulative exposure within all currently protected planning units with that of all high priority areas from Scenario 5. The proportional difference in cumulative exposure represented the theoretical ecological cost associated with continuing to protect areas of sub-optimal exposure.



**Fig. 17** Spatial distributions of four Marxan inputs: a) conservation targets (species of concern), b) risk (human land modification), c) climate exposure, and d) climate connectivity

**Table 2** Marxan parameters for each conservation scenario

<b>Scenario</b>	<b>Goal</b>	<b>Risk</b>	<b>Existing Protected Areas Included?</b>
<b>1</b>	Minimize exposure	Ignored	Yes
<b>2</b>	Maximize connectivity	Ignored	Yes
<b>3</b>	Minimize exposure	Accounted for	Yes
<b>4</b>	Maximize connectivity	Accounted for	Yes
<b>5</b>	Minimize exposure	Accounted for	No

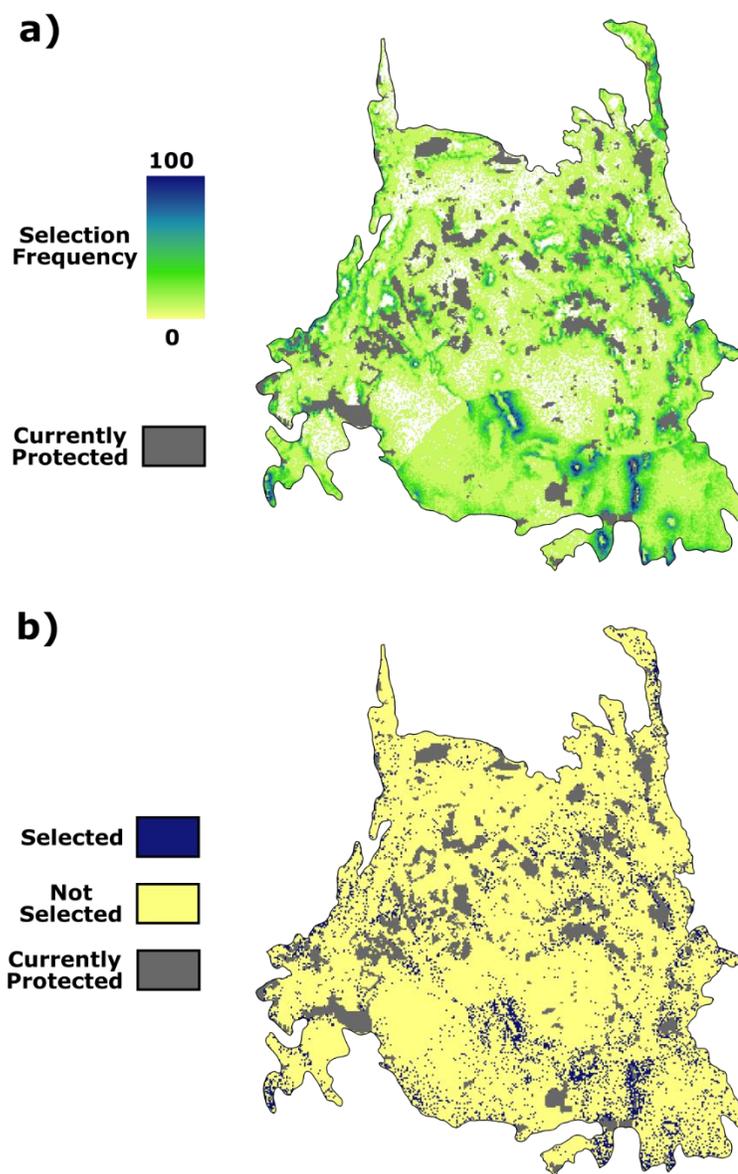
## RESULTS

Under the first management scenario aimed at minimizing climate exposure, patterns in modeled conservation priority indicated the selection of new areas that have both low climate exposure also meet species representation targets. In Scenario 1, areas with the highest selection frequencies generally corresponded to areas with the lowest climate exposure, though planning units were more often selected where the diversity of targeted wildlife species was highest, particularly the southeastern and northeastern portions of the region (Figure 18a). The mean exposure value of these high priority planning units was about 9.3 times higher than planning units with the lowest 5% of exposure values. This difference directly reflects the trade-off between minimizing exposure and protecting one's conservation targets. The areas selected in the best (lowest-exposure) solution showed similar patterns to those in selection frequency (Figure 18b). All Marxan runs under Scenario 1 – including the lowest-exposure solution – met the representative conservation targets for all species.

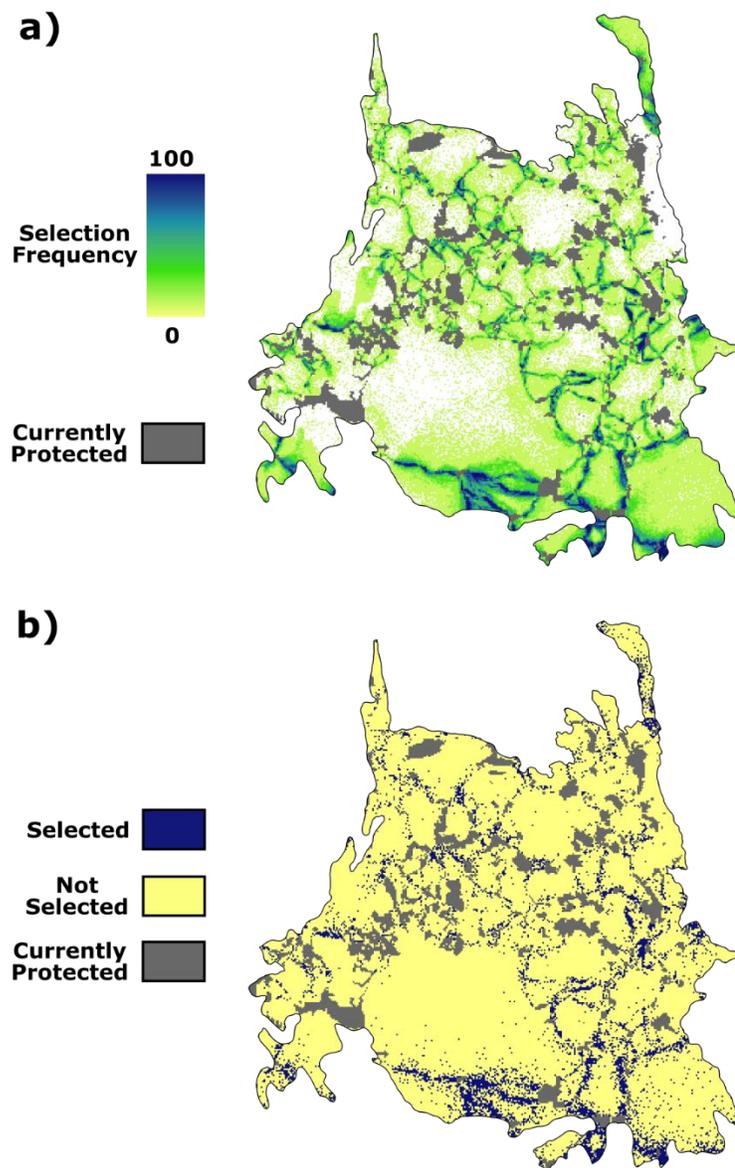
Results from the maximum connectivity scenarios similarly achieved protected area solutions that combined the overlapping patterns of connectivity and target richness. Conservation priority again varied across the landscape in a manner that reflected the richness of wildlife targets, with higher selection frequency in the southern and eastern

portion of the region (Figure 19a). Mirroring the patterns in selection frequency, the planning units selected during the best (highest connectivity) Marxan run solution primarily included long climate corridors in the region's southern reaches (Figure 19b). As with Scenario 1, species representation targets were met for all 100 Marxan runs. Throughout the entire region, a significant number of the modeled high priority corridors overlapped or adjoined areas also predicted as being of high priority based on minimizing climate exposure (Figure 20).

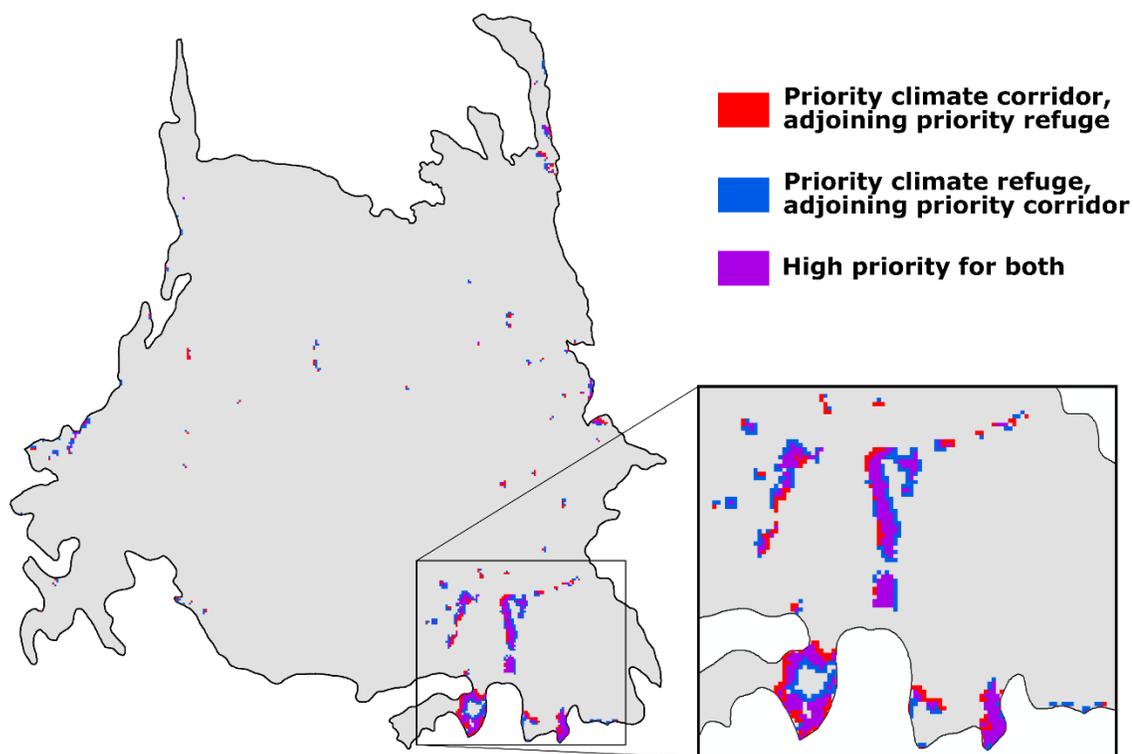
Accounting for the risk of land modification in the prioritization process caused certain areas to be selected for protection more and less frequently, generating greater spatial variation in resulting conservation priority areas. When maximizing connectivity, the effect of incorporating risk on conservation priority was less widespread than when minimizing climate exposure (Figure 21). This was evidenced by the greater number of planning units in Figure 21b that exhibited no change in their selection frequency, relative to Figure 21a. For the scenario minimizing exposure, the inclusion of risk led to a slight decrease in the cumulative climate exposure of the most highly selected planning units (0.576%), as well as a slight increase in the exposure of those selected in the best solution (0.767%). Changes in cumulative connectivity values when accounting for risk were similarly small for the best solution (1.065% increase) and larger for high priority areas (0.398% decrease). These proportional differences in exposure and connectivity following the inclusion of risk can be directly interpreted as ecological costs and benefits incurred in the conservation process, a trade-off between accounting for direct factors in climate change resilience and addressing additional socioecological influences on conservation success.



**Fig. 18** Marxan outputs for conservation scenario #1 for minimizing climate exposure: a) selection frequency and b) least-exposure run solution



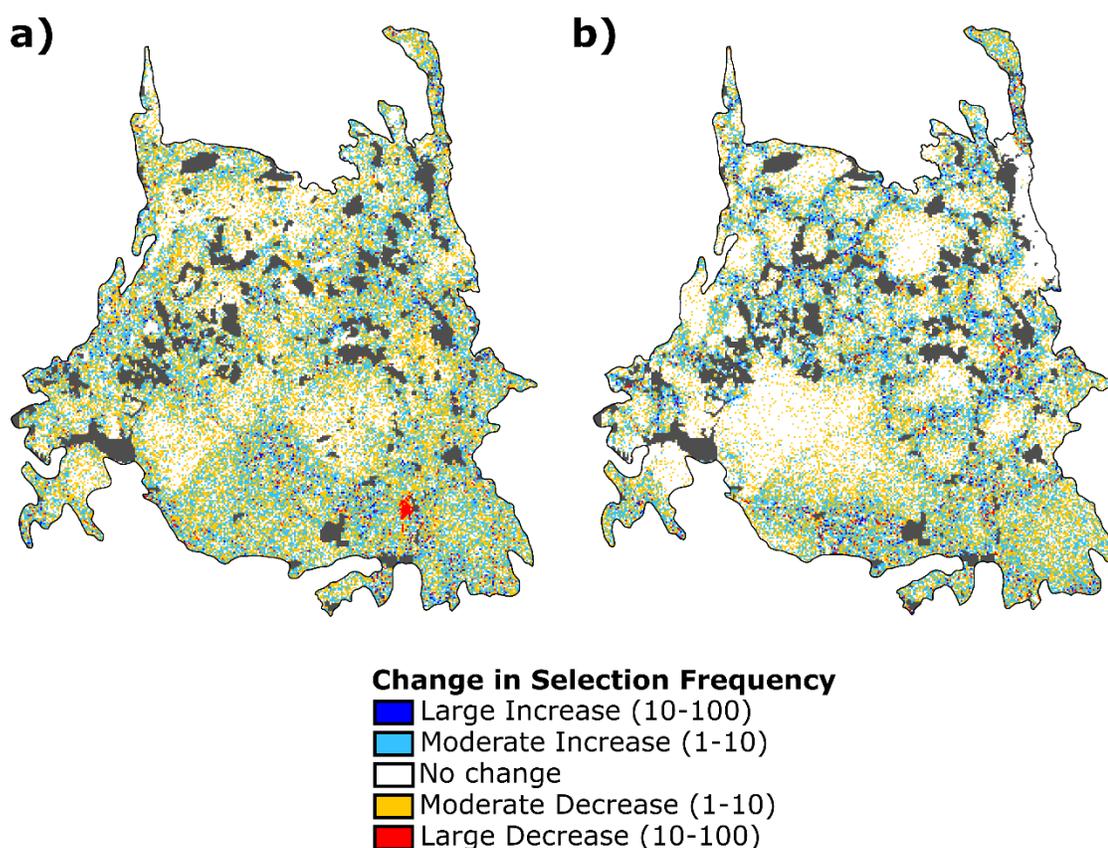
**Fig. 19** Marxan outputs for conservation scenario #2 for maximizing climate connectivity: a) selection frequency and b) most-connectivity run solution



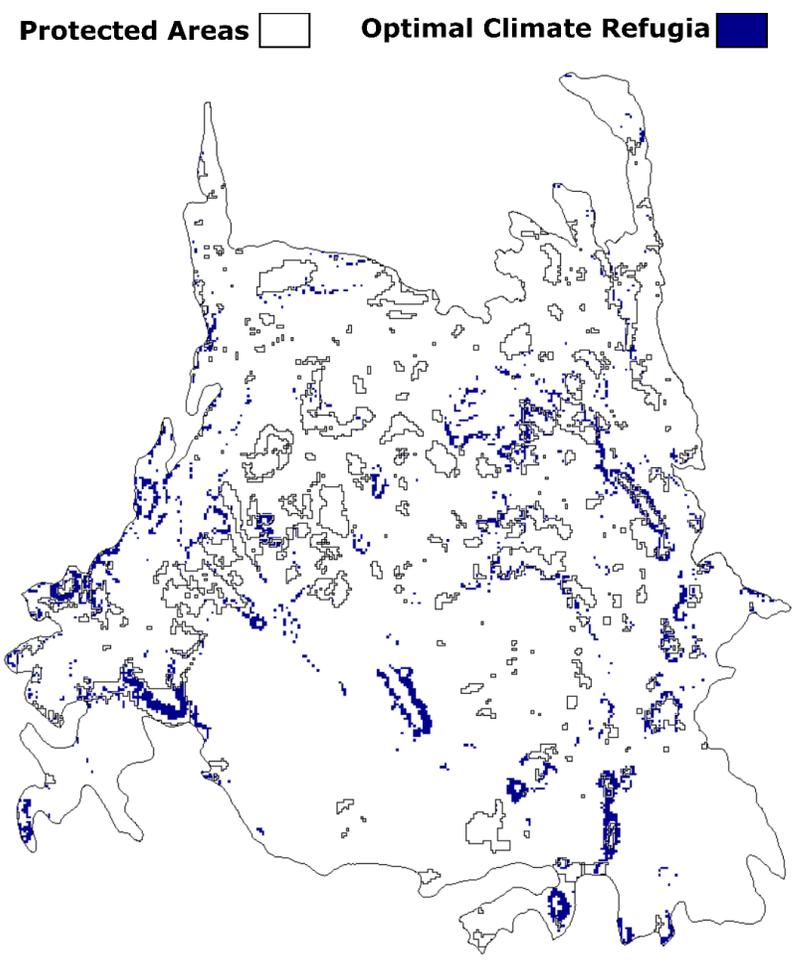
**Fig. 20** Adjoining high priority areas (climate corridors and climate refugia)

By ignoring the current protected area status of the planning units, prioritization aimed at minimizing climate exposure was used to identify optimal climate refugia and evaluate the relative resilience of currently protected areas to climate impacts. Only 22.89% of optimal climate refugia (top 5% by selection frequency) fell within currently protected planning units (Figure 22). These optimal climate refugia overlapped more widely with the lowest-exposure areas, with 90.98% of refugia area located within an extent of low exposure areas equivalent in size to the existing protected area network. Currently protected planning units also varied in their overall climate exposure values and in their conservation priority following the inclusion of species targets and risk. Both climate exposure and modeled conservation priority across the entire network of

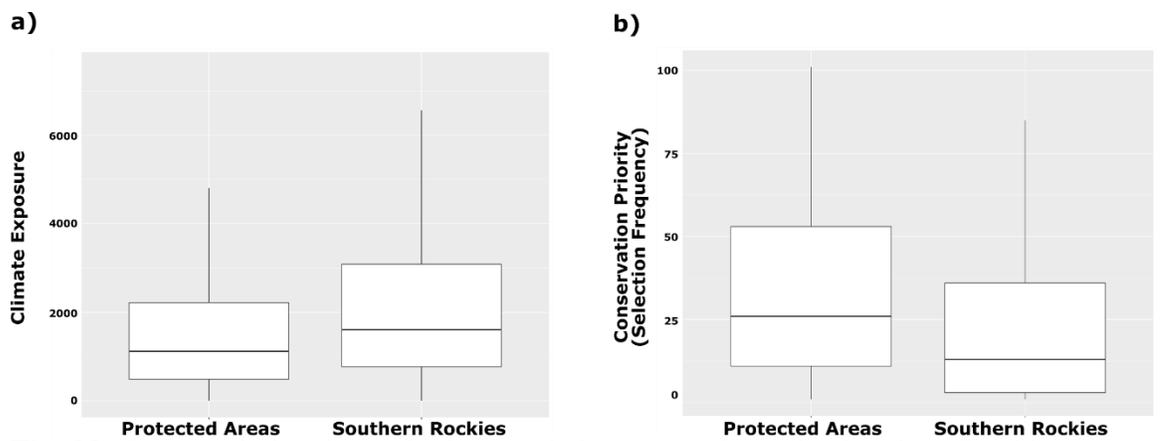
protected planning units was comparable to that across the entire Southern Rockies region (Figure 23), though mean priorities were higher and mean exposure lower in the protected areas relative to the broader region. While some contiguous protected areas had higher exposure and lower priority than the regional averages, many demonstrated the opposite pattern (Figure 24). Variation in conservation priority within individual protected areas was considerably greater than variation in exposure.



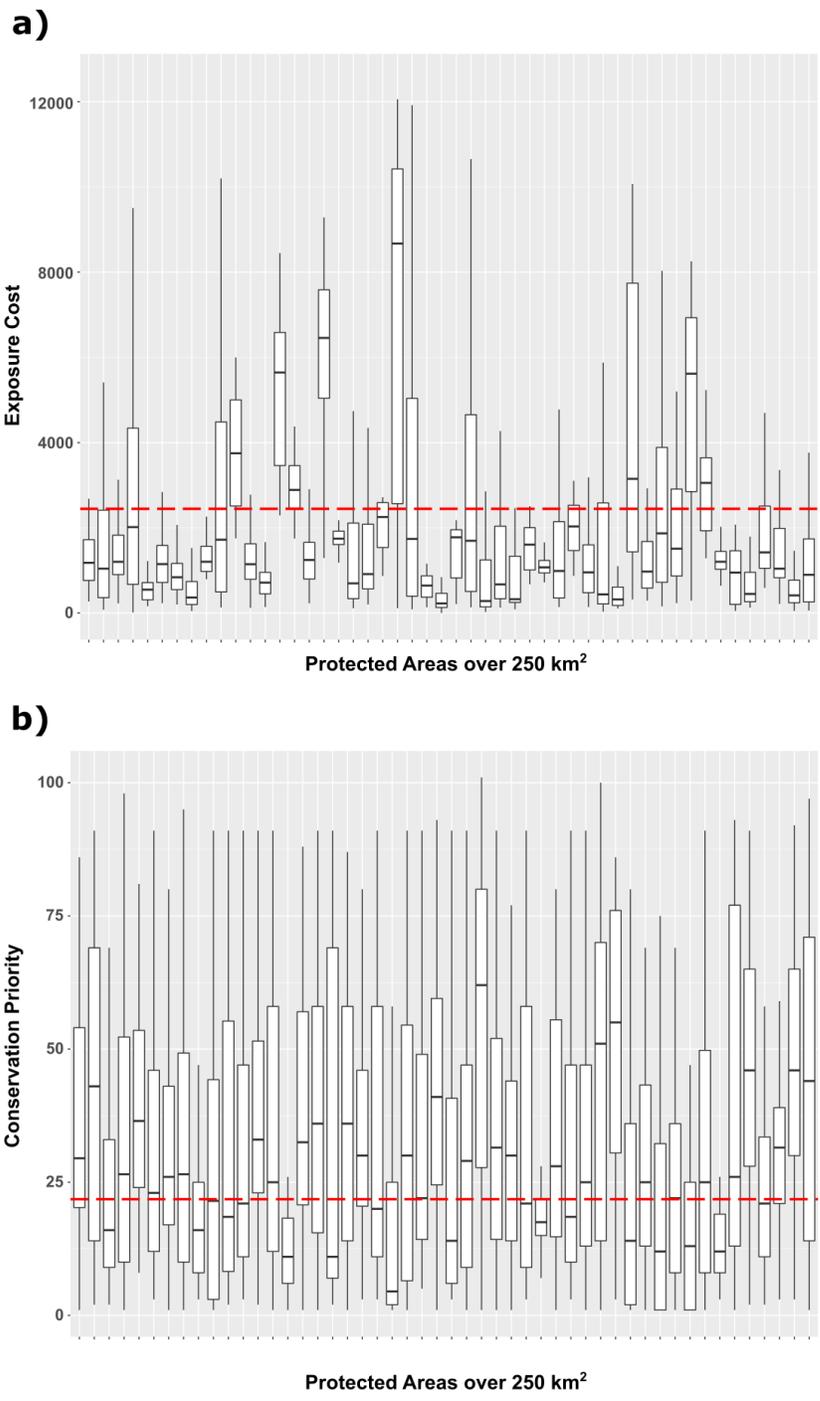
**Fig. 21** Change in conservation priority (selection frequency) when accounting for risk and ignoring risk in scenarios for a) minimizing climate exposure and b) maximizing connectivity



**Fig. 22** Optimal climate refugia distribution relative to currently protected planning units



**Fig. 23** Protected planning unit characteristics versus the entire Southern Rockies region, comparing a) climate exposure and b) modeled conservation priority



**Fig. 24** The a) exposure cost and b) modeled conservation priority of the 50 largest contiguous protected areas, each over 250 km<sup>2</sup>. Red dashed lines represent the average of each metric across the entire Southern Rockies region

## DISCUSSION

Here I have presented a framework for systematically integrating climatic vulnerabilities into protected area conservation. Not only does this framework allow one to merge multiple conservation objectives – including threatened species protection and reduction of climate vulnerabilities – into the planning process, its outcomes are improved by doing so. Through achieving a balance between multiple species protection and broader ecological costs, tools such as Marxan can greatly focus one's management options towards the areas with the highest potential for positive outcomes.

With the primary aim of building a framework for enhancing the climate resilience of protected area networks, I modeled conservation priorities in the Southern Rockies region as a combination of both biotic and abiotic management goals. I identified potential networks of climate refugia and corridors that simultaneously house species of concern. Patterns of relative conservation priority across the landscape aligned closely to the climate resilience metric used in the selection process – exposure or connectivity – but also reflected the diversity of species targets. Though patterns in priority based on exposure and connectivity showed little similarity, I was able to further extract areas that demonstrated high priority across those two contrasting conservation scenarios by looking at the overlap between the highest climate refugia and corridors.

The methods that I have presented here also provide a means to account for a wider variety of risks in addition to climate change. As it was not the primary purpose of this study to predict human responses to climate change, the metric I chose to simulate the probability of conservation failure (percentage of modified land cover) was relatively simple and did not account for the full variety of ecological risks within the region, such

as oil and gas development (Copeland *et al.*, 2009; Bryce *et al.*, 2012). Importantly, however, even this spatially-confined stressor still had a clear impact on the distribution of climate-based conservation priorities, demonstrating both the importance of accounting for risk and the ability of my framework to do so. Landscape managers seeking to apply the results of this prioritization framework toward on-the-ground decision making may be interested more thoroughly evaluating the ecological and social factors contributing to conservation success in a manner that is most relevant in their jurisdictions. Despite the direct role that risks can play in this type of conservation decision making, understanding and quantifying the spatial distributions of future probabilities of conservation success and failure remains an area of critical research need (Williamson & Schwartz, 2017).

The existing protected area system of the Southern Rockies has demonstrated moderate but highly variable levels of vulnerability to climate change. The variability in exposure and priority between and within areas of current protection suggests that certain protected areas are projected to experience more or less intense pressures from climate change. Overall, climate exposure was observably lower in current protected areas than the average across the region, indicating that they are slightly less vulnerable to climate shifts due to their greater adaptability. However, the lack of overlap between current protected areas and optimal climate refugia demonstrated here suggests improvements that could be made upon the existing protected area system in order to reduce vulnerability while meeting the set conservation targets.

By concentrating the selection of new protected areas on places where climate exposure is low and connectivity is high, conservation practitioners could enable species

to more effectively shift their distributions in response to novel climate conditions, allowing broader systems to remain resilient through adaptation and transformation (Walker *et al.*, 2004; Sayer *et al.*, 2013). Particularly under a changing climate, the sustainability of any given socioecological system benefits from an understanding of the system's limit and barriers to adaptation, as well as explicit acknowledgement of the need for transformability (Preston *et al.*, 2013). Where ecological shifts due to climate change are seemingly inevitable, it may be necessary to focus conservation on facilitating those shifts, aiming the trajectories of the systems toward more desirable states (Folke *et al.*, 2010; Preston *et al.*, 2013; Hobbs *et al.*, 2014).

## CHAPTER 4

### SUMMARY AND CONCLUSIONS

Efforts must still be made to explicitly account for climate change in conservation decision making processes (Jones *et al.*, 2016; Reside *et al.*, 2017). However, it remains uncertain how best to integrate climate change impacts into the ongoing practices of creating and managing protected landscapes (Game *et al.*, 2011; Hannah *et al.*, 2016). While past studies have made general management recommendations for buffering protected ecological resources against climate change impacts, including the conservation of climate change refugia and landscape corridors, paths toward their actual implementation have been limited (Hannah *et al.*, 2016; Morelli *et al.*, 2016). Across broad, diverse regions such as the Southern Rockies and the other areas of the LCC network, landscape conservation remains driven by pre-existing management needs, such as protection of individual species of concern (e.g. mule deer, elk) and other focal resources (e.g. sagebrush steppe ecosystems, cultural landscapes). Furthermore, the capability to successfully conserve a region's focal resources depends on many factors aside from climate change impacts, such as the impacts of human development. Any efforts to effectively implement one of the recommended strategies for promoting climate resilience (refugia, corridors, etc.) should incorporate these additional factors to boost overall effectiveness in the longer term.

In order to make conservation decisions in direct response to climate change, landscape managers must first understand how climate change vulnerabilities are spatially and temporally distributed (Dawson *et al.*, 2011). In Chapter 2, I demonstrated how one can model climate change exposure and connectivity so as to identify areas of

the landscape that are generally at the lowest risk of being altered by climate shifts. Since these metrics of exposure and connectivity are often based entirely on individual climate variables, they do inevitably ignore the multitude of biotic and abiotic landscape characteristics that contribute to the individual vulnerabilities of species and ecosystems to climate change, including edaphic, climatic, and anthropogenic conditions (Dawson *et al.*, 2011). However, protected area management occurs across broad landscapes that span numerous unique and diverse components. Limitations on time and resources make it so that the case-by-case vulnerability cannot be thoroughly quantified across all those components. At the same time, the gathering of additional information through assessment and monitoring does not necessarily improve conservation outcomes (McDonald-Madden *et al.*, 2010). This suggests that it would be prudent to move forward with climate-based decision making using coarse-filter vulnerability assessments, especially where individualized assessments are lacking. What generalized metrics of exposure and connectivity lack in specificity, they make up for in their broad applicability and adaptability. By quantifying climate vulnerability across one's multiple systems using only the few variables that are most broadly and ecologically meaningful, one could rapidly and cost-effectively propose conservation of various combinations of resources within the region. Recommendations produced by this broad approach could then act as a starting point, from which managers could tailor their treatment of vulnerability in a way the best fits regional conservation goals.

As a second step for improving climate-driven conservation outcomes, landscape managers can improve upon existing protected area networks by adaptively combining generalized metrics of climate change vulnerability with the distributions of their

conservation targets. In Chapter 3, I showed how one can identify priority areas for conserving ecological features of the landscape under various scenarios aimed at protecting either climate refugia or landscape corridors. I demonstrated how priorities can shift as a result of changing one's primary conservation objective (e.g. minimizing exposure vs. maximizing connectivity), accounting for risks to conservation success (e.g. anthropogenic land modification), and including existing protected areas. In the process, I assessed the potential resilience of existing protected areas by evaluating their relative climate exposure and their overlap with optimized climate refugia. Importantly, this research was mainly aimed at prioritizing where to undergo certain conservation actions, a significant but small piece of a much broader conservation puzzle. As with any individual decision support framework, the spatial prioritization methods that I have described would best be utilized in combination with complementary frameworks that are better suited for answering the other key conservation questions, such as how to conserve the resources in the high priority areas (Schwartz *et al.*, 2017). For instance, spatial conservation tools can provide means for identifying climate refugia, but other decisions must be made in which specific management actions to take (e.g. restoration, habitat protection, assisted migration). Addressing the various issues and challenges confronted in conservation decision making requires a holistic set of decision making approaches that explicitly acknowledge project purposes and limitations (Game *et al.*, 2013; Schwartz *et al.*, 2017).

In order to move forward with conservation activities that explicitly and systematically account for the impacts of climate change, further research is necessary in a few key areas. Firstly, while the research I have outlined builds on existing decision

support frameworks by prioritizing landscape conservation based on assessed vulnerabilities and multiple conservation targets, improvements to model inputs would greatly enhance the robustness and real-world applicability of such frameworks. Each model of climate exposure, connectivity, and conservation priority comes with limitations in data availability and suitability, such as the lack of comprehensive fine-scale climate data needed for widely identifying climate microrefugia (Ashcroft, 2010; Morelli *et al.*, 2016). Secondly, there is an increasing recognition of the need to account for indirect effects on the likelihood of conservation success, particularly those associated with human responses to climate change (Game *et al.*, 2013; Chapman *et al.*, 2014; Jones *et al.*, 2016). For instance, changes in patterns of precipitation could partially drive patterns in human development, promoting land uses that degrade habitats currently available for conservation (Faleiro *et al.*, 2013). Despite the risk that indirect effects pose to conservation, spatial quantification of the factors contributing to conservation action success is an area in need of greater exploration. Finally, further efforts to aid in climate-based conservation must be made to better integrate with existing landscape management contexts, as efficient conservation depends on making use of minimal resources to yield maximum returns on management investments (Bottrill *et al.*, 2008; Game *et al.*, 2013; Schwartz *et al.*, 2017). Through more direct collaboration with landscape managers and stakeholders within the study region, conservation problems and challenges become more clearly defined, ideally resulting in decision support frameworks that are best suited to the stakeholders, and to the landscapes under consideration.

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## APPENDICES

Appendix A List of the 31 wildlife species of interest found in the Southern Rockies region used for Marxan analyses

<b>Binomial</b>	<b>Common Name</b>	<b>IUCN Status</b>	<b>Class</b>	<b>Order</b>	<b>Family</b>
<b>Anthus spragueii</b>	Sprague's Pipit	Vulnerable	Aves	Passeriformes	Motacillidae
<b>Aspidoscelis neotesselata</b>	Colorado Checkered Whiptail	Near Threatened	Reptilia	Squamata	Teiidae
<b>Bison bison</b>	American Bison	Near Threatened	Mammalia	Cetartiodactyla	Bovidae
<b>Calcarius ornatus</b>	Chestnut-collared Longspur	Near Threatened	Aves	Passeriformes	Calcariidae
<b>Calidris pusilla</b>	Semipalmated Sandpiper	Near Threatened	Aves	Charadriiformes	Scolopacidae
<b>Centrocercus minimus</b>	Gunnison Grouse	Endangered	Aves	Galliformes	Phasianidae
<b>Centrocercus urophasianus</b>	Greater Sage Grouse	Near Threatened	Aves	Galliformes	Phasianidae
<b>Chaetura pelagica</b>	Chimney Swift	Near Threatened	Aves	Caprimulgiformes	Apodidae
<b>Charadrius montanus</b>	Mountain Plover	Near Threatened	Aves	Charadriiformes	Charadriidae
<b>Charadrius nivosus</b>	Snowy Plover	Near Threatened	Aves	Charadriiformes	Charadriidae
<b>Colinus virginianus</b>	Northern Bobwhite	Near Threatened	Aves	Galliformes	Odontophoridae
<b>Contopus cooperi</b>	Olive-sided Flycatcher	Near Threatened	Aves	Passeriformes	Tyrannidae
<b>Cynomys parvidens</b>	Utah Prairie Dog	Endangered	Mammalia	Rodentia	Sciuridae
<b>Dipodomys spectabilis</b>	Banner-tailed Kangaroo Rat	Near Threatened	Mammalia	Rodentia	Heteromyidae
<b>Euphagus carolinus</b>	Rusty Blackbird	Vulnerable	Aves	Passeriformes	Icteridae
<b>Gymnogyps californianus</b>	California Condor	Critically Endangered	Aves	Cathartiformes	Cathartidae
<b>Gymnorhinus cyanocephalus</b>	Pinyon Jay	Vulnerable	Aves	Passeriformes	Corvidae
<b>Haemorhous cassinii</b>	Cassin's Finch	Near Threatened	Aves	Passeriformes	Fringillidae

## Appendix A (cont.)

<b>Binomial</b>	<b>Common Name</b>	<b>IUCN Status</b>	<b>Class</b>	<b>Order</b>	<b>Family</b>
<b>Heloderma suspectum</b>	Gila Monster	Near Threatened	Reptilia	Squamata	Helodermatidae
<b>Kinosternon sonoriense</b>	Sonoyta Mud Turtle	Near Threatened	Reptilia	Testudines	Kinosternidae
<b>Lithobates chiricahuensis</b>	Chiricahua Leopard Frog	Vulnerable	Amphibia	Anura	Ranidae
<b>Lithobates onca</b>	Relict Leopard Frog	Endangered	Amphibia	Anura	Ranidae
<b>Melanerpes erythrocephalus</b>	Red-headed Woodpecker	Near Threatened	Aves	Piciformes	Picidae
<b>Plethodon neomexicanus</b>	Jemez Mountains Salamander	Near Threatened	Amphibia	Caudata	Plethodontidae
<b>Pseudemys gorzugi</b>	Rio Grande Cooter	Near Threatened	Reptilia	Testudines	Emydidae
<b>Spilogale putorius</b>	Eastern Spotted Skunk	Vulnerable	Mammalia	Carnivora	Mephitidae
<b>Strix occidentalis</b>	Spotted Owl	Near Threatened	Aves	Strigiformes	Strigidae
<b>Sylvilagus cognatus</b>	Manzano Mountain Cottontail	Endangered	Mammalia	Lagomorpha	Leporidae
<b>Terrapene ornata</b>	Ornate Box Turtle	Near Threatened	Reptilia	Testudines	Emydidae
<b>Toxostoma bendirei</b>	Bendire's Thrasher	Vulnerable	Aves	Passeriformes	Mimidae
<b>Vireo bellii</b>	Bell's Vireo	Near Threatened	Aves	Passeriformes	Vireonidae