Identifying and mapping climatically stable macro- and microrefugia in New Mexico

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Year 1 Final Report

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Accessory Documents:

Supplemental File 1. Data Catalogue

This file lists the primary sources for data used in the assessment of climate refugia. Under each primary source is a list of derived spatial data layers.

Supplemental File 2.

Final selection of Refugia Indicators generated for use in an analysis for New Mexico. For each indicator, this table provides a definition, data source, calculations used to generate metric (if applicable), and citations for sources or justifying articles. We also include information on the nature of the metric (positive or negative indicator) for identifying climate refugia.

1. Overview

As a first step for this project, we reviewed the literature to better understand current knowledge with respect to identifying indicators of climate change and climate change refugia. Indicators of climate change and related land conditions are used to describe status and trends for key phenomena in ecosystems and must be measurable either directly or indirectly (e.g., through the use of proxies; Kenny et al. 2015). Similarly, indicators of climate change refugia must relate to potential for areas within a landscape to provide conditions consistent enough or proximate enough to existing species' habitat that species are able to use the area and persist within an otherwise inhospitable landscape.

Recent years have seen a surge in studies and systems developed to track and measure climate change impacts. Several governments and governmental agencies have adopted specific climate change indicators to inform national and regional priorities. Simultaneously, the practical application of climate change refugia has gained interest and support from a range of scientists and managers. The next sections review the state of knowledge and primary best practices identified in the literature. From this review, we determined which climate change refugia indicators are likely to be most meaningful for identifying the relative importance of existing conservation areas and identify new areas that could potentially support species persistence under climate change.

2. Review of Climate Indicators

Considerable effort has been invested at national and international levels to identify metrics that will provide meaningful information on climate impacts. We conducted a review of the literature to identify climate change indicators for assessing ecosystems and species. We began by searching google scholar for relevant articles using the search terms, “climate change”, “indicators”, “indices”, and “climate change monitoring”, and gathered current government and international guidelines that outline climate change indicators. We used the cited literature from these sources to identify additional sources. Table 1. lists indicators identified during the literature review that potentially have direct relevance to species management. We classified these indicators into broad categories representing primary metrics of interest. The categories of biodiversity, plant growth, and fire contained the greatest number of unique indicators. Biodiversity is commonly measured in ecological studies and is an obvious target for conservation. Relatedly, Sundstrom et al. 2013 propose using functional group diversity to measure potential climate impacts. A number of systems consider phenological metrics, including the timing of animal movements or breeding activity and plant emergence and growth. Climate extremes were also considered by a majority of studies reviewed, although most studies focused on slightly different metrics. In general, the risk of extreme events and the associated high cost of extreme events drove the inclusion of many of these metrics. Drought was also addressed by multiple studies, suggesting that changes in drought patterns are likely to result in corresponding undesirable changes in natural communities.

Table 1. Summary of major themes found in literature describing climate change indicators. Below is a list of indicators that relate to natural resources, especially wildlife and ecosystems. Many sources reviewed and proposed indicators that covered multiple other sectors (e.g., society, economy, agriculture); these indicators are not included here.

Biotic		
	Animal Migration and Breeding	
		Calling and breeding of frogs (Rose et al. 2023)
	Animal Migration and Seasonal Distribution	
		Bird wintering range: latitude of bird center of abundance (Weltzin et al. 2020)
	Functional Groups	
		Number of functional groups within a spatial aggregation (Sundstrom, Allen, and Barichievy 2013)
		Overall number of functional groups (Sundstrom, Allen, and Barichievy 2013)
		Redundancy of functional groups across aggregations (Sundstrom, Allen, and Barichievy 2013)
	Biodiversity	
		Bird diversity (Lorente et al. 2020)
		Diatom assemblage composition - diatom fossil record (Rose et al. 2023)
		Distribution of tree species (Lorente et al. 2020)
		Forest tree and fauna biodiversity status and trends (Anderson et al. 2021)
		Genetic diversity (Lorente et al. 2020)
		Habitat to support diversity (Lorente et al. 2020)
		Invertebrate assemblage composition (Rose et al. 2023)
		Phytoplankton levels (Rose et al. 2023)
		Shrub diversity (Lorente et al. 2020)
	Plant Growth/Productivity	
		Aboveground live biomass/unit area (Anderson et al. 2021; Ojima et al. 2020)
		Annual growth rings (Lorente et al. 2020)
		Change in biomass and wood volume (Lorente et al. 2020)
		Net primary productivity (NPP) (Anderson et al. 2021; Lorente et al. 2020)
		Percent annual loss of living tree biomass (Lorente et al. 2020)
		Success and failure of assisted migration blocks (Lorente et al. 2020)
		Success and failure of natural forest regeneration postharvest and post disturbance (Lorente et al. 2020)
		Tree cone and seed crop production (Lorente et al. 2020)
	Insects and Pathogens	
		Forested area affected by insects or disease (Anderson et al. 2021)
		Incidence of forest pathogens (Lorente et al. 2020)
		Distribution of pest species (Lorente et al. 2020)
	Land Cover Area and Extent	
		Forest area based on forest cover only (Anderson et al. 2021)

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		Land cover extent (Ojima et al. 2020)
		Forestland area by land use (Anderson et al. 2021)
Climate		
	Precipitation	
		Standardized Precipitation Index (Peters-Lidard 2021)
		Trends in annual and seasonal precipitation (Peters-Lidard 2021)
		Total precipitation (Peters-Lidard 2021)
	Temperature	
		Absolute change in mean summer maximum temperatures (Rojas et al. 2018)
		Duration heat stress (Weltzin et al. 2020)
		End heat stress (Weltzin et al. 2020)
		Start heat stress (Weltzin et al. 2020)
	Drought	
		Climate Moisture Index (CMI) (Lorente et al. 2020)
		Climatic Water Deficit (CWD) (Rojas et al. 2018)
		Evaporative Demand Drought Index (EDDI) (Ojima et al. 2020)
		Palmer Drought Severity Index (PDSI) (Lorente et al. 2020)
		Soil Moisture Index (SMI) (Lorente et al. 2020)
		Soil Water Availability (SWA) (Barnard et al. 2021)
		Standardized Precipitation-Evapotranspiration Index (SPEI) (Barnard et al. 2021)
		Water Balance Deficit (Anderson et al. 2021)
	Extreme/Heavy precipitation	
		Exceedance dates for percentiles of cumulative precipitation (Weltzin et al. 2020)
		Annual rainfall delivered by large 1-day events (USGCRP Indicators Catalog)
		Total precipitation delivered in the top 1% of all days with precipitation (Peters-Lidard 2021)
	Extreme Storms	
		Lightning (Lorente et al. 2020)
		Thunderstorms (Lorente et al. 2020)
		Windthrow (Lorente et al. 2020)
	Extreme temperatures	
		Cumulative annual heating (Weltzin et al. 2020)
		Frequency of extreme summer temperatures (Rojas et al. 2018)
	Heat Waves	
		Heat wave season length (USGCRP Indicators Catalog)
		Number of heat waves (USGCRP Indicators Catalog)
	Non-analogous (Novel) Conditions	
		Non-analogous climate conditions (Carroll et al. 2018)
Disturbances		
	Fire	
		Annual area burned (Anderson et al. 2021; Lorente et al. 2020)

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		Duration of fire season (Lorente et al. 2020; Weltzin et al. 2020)
		End of fire season (Lorente et al. 2020; Weltzin et al. 2020)
		Fire refugia (Rojas et al. 2018)
		Fire severity (Anderson et al. 2021)
		Number of large fires (Anderson et al. 2021; Lorente et al. 2020)
		Peak fire season (Lorente et al. 2020; Weltzin et al. 2020)
		Start of fire season (Lorente et al. 2020; Weltzin et al. 2020)
	Anthropogenic	
		Exposure to recreational activities (Rojas et al. 2022)
Phenology		
	Frost-free Season	
		Duration of frost-free season (Kenney et al. 2016; Weltzin et al. 2020)
		End of frost-free season (Weltzin et al. 2020)
		Start of frost-free season/spring (Weltzin et al. 2020; USGCRP Indicators Catalog)
		Spring thaw date (Weltzin et al. 2020)
	Frost Season	
		Duration of frost season (Weltzin et al. 2020)
		End of frost season (Weltzin et al. 2020)
		Fall freeze date (Weltzin et al. 2020)
		Start of frost season (Weltzin et al. 2020)
	Length of Growing Season	
		Duration of vegetation index transitions (Weltzin et al. 2020)
		Standard and nonstandard degree days (Lorente et al. 2020)
	Plant Growth Emergence	
		Peak vegetation index values (Weltzin et al. 2020)
		Start of vegetation index transitions (Weltzin et al. 2020)
		End of vegetation index transitions (Weltzin et al. 2020)
		Timing of spring onset (bud burst) (Lorente et al. 2020)
		Timing of spring onset (first leaf, first bloom) (Rose et al. 2023; Weltzin et al. 2020)
Hydrology		
	Groundwater	
		Annual average groundwater levels (Peters-Lidard 2021)
	Snow cover/Snow Water Equivalent	
		Date of maximum snow water equivalent (Peters-Lidard 2021)
		Magnitude of maximum snow water equivalent (Peters-Lidard 2021)
		Total snow-covered area (Peters-Lidard 2021)
	Stream Integrity	
		Level of naturalness (proportion of impervious surfaces) (Rojas et al. 2018)
		Level of naturalness (proportion of natural landcover) (Rojas et al. 2018)
	Streamflow	

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		Date of center of volume (COV) of streamflow (Peters-Lidard 2021)
		Normalized annual mean streamflow (Peters-Lidard 2021)
		Seven-day average minimum daily streamflow (Peters-Lidard 2021)
		Three-day high streamflow (Peters-Lidard 2021)
	Water Balance	
		Evapotranspiration (ET) (Peters-Lidard 2021)

Sources:

3. Review of Climate Refugia Indicators

One strategy to reduce climate impacts to natural communities involves the identification of refugia (localized areas that are relatively buffered from environmental change over time; Cartwright 2018). Climate refugia are areas that allow species to persist in situ or to which species can retreat or colonize when surrounding conditions are otherwise uninhabitable (Keppel et al. 2012, 2015; Rojas et al. 2018). From a historic perspective, climatic refugia are large regions where organisms have been able to take refuge, for example during the glacial advances and retreats of the Pleistocene (2.5 million years ago to 11,500 years ago), providing a source population for colonization during more favorable climatic periods (Hewitt 2000; Davis and Shaw 2001; Dobrowski et al. 2011). On a more local temporal or spatial scale, climate refugia are areas that remain suitable for species even when regional conditions may not support their persistence. These “microrefugia” or “cryptic refugia” (Dobrowski et al. 2011) commonly support isolated, low-density populations of species beyond their climatically reconstructed range boundaries and may allow for the recolonization of depopulated areas via local dispersal after the recurrence of favorable conditions (McLachlan et al. 2005; Pearson 2006; Birks and Willis 2008; Provan and Bennet 2008).

This effort considers both macro- and microrefugia measures. Climate refugia are considered at these two scales: 1) a coarse-filter representation that is often measured through regional changes in climate conditions, and 2) a fine-filter representation that considers site-specific characteristics that may influence local climate (Carroll et al. 2017). The approach taken here, to produce and compile data for New Mexico, incorporates both coarse and fine filters among a suite of indicators that might point to areas (macro- and microrefugia) that will help species persist in the face of unfavorable conditions presented by climate change.

Macrorefugia are defined as areas with sustained climatic suitability along broad spatial and temporal gradients (Stralberg et al. 2018). Microrefugia are identified as conditions that allow a decoupling of local climate conditions from the surrounding landscape (Ashcroft 2010; Dobrowski 2011; Stralberg et al. 2018). A first step towards identifying climate refugia indicators for New Mexico was to review the literature and compile current knowledge and applications of this concept for wildlife and wildlife habitat (Table 2). From this list, we identified candidates for use in our analysis of New Mexico landscapes (Table 3). These candidate indicators will be presented to the New Mexico Department of Game and Fish (NMDGF) and other collaborators and experts to vet their utility as broadly applicable indicators of refugia. We will analyze the resulting list to identify which indicators best represent biodiversity and other characteristics of interest using linear regression. Indicators associated with areas of known interest (high biodiversity, presence of Species of Conservation Concern) will then be used in Zonation software to identify potential refugia.

Literature Review

To identify relevant literature, we searched databases for papers that included the terms climate change + refugia, habitat refugia, ecosystem refugia, microclimate refugia, and macroclimate refugia. Topographic indicators were the predominant focus of the papers found by the above literature search (Table 2). Depending on the topic of the paper, other aspects relating to biological diversity or composition were often included as important measures of climate refugia. We do not review these non-target measures here.

Table 2. List of indicators identified in our review of the literature focused on climate change refugia. Papers that focused on the identification of climate change refugia are cited in this list. Indicators are listed as they are presented in each paper. Some studies focused on a concept in its entirety (landforms) and others focused on certain aspects of a concept (percent valleys). Some variables are specific to certain ecosystems. Importantly, this list does not include variables listed in papers assessing species distributions or analyzing climate resilience/resistance. However, these papers were considered during the final selection of refugia indicators.

Category	Metric	**Citations**
Biological diversity		
	Species Richness	Carroll et al. 2017; Carroll and Noss 2020
	Ecotypic Diversity	
Carbon		
	Aboveground Carbon	Carroll and Noss 2020
	Soil Carbon	
Climate		
	Climate Connectivity	Carroll and Noss 2020; Dobrowski 2011; Stark and Fridley 2022; Stalberg et al. 2018; Rojas et al. 2013; Haire et al. 2022
	Interpolated Mean Annual Temperature	
	Mean Annual Temperature	
	Mean Annual Maximum Temperature	
	Mean Annual Minimum Temperature	
	Mean Seasonal or Quarterly Temp	
	Macroclimate Mean Annual Temperature	
	Microclimate Mean Annual Temperature	

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	Maximum Synoptic Temperature	
	Minimum Synoptic Temperature	
	Temperature (Hottest-Coldest) Difference	
	Total Precipitation Per Season or Quarter	
	Total Annual Precipitation	
Climate Extremes		
	Extreme Summer Temp	Ashcroft et al. 2012; Rojas et al. 2013
	Highest Mean Ann Temp	
	Lowest Mean Ann Temp	
	Frequency of Drought	
	Length of Drought	
	Number of Heat Waves	
	Snow vs. Rain Proportion	
Climate Index		
	Backward Climatic Velocity	Ashcroft et al. 2012; Carroll et al. 2017; Carroll and Noss 2020; Haire et al. 2022; Stalberg et al. 2018
	Forward Climatic Velocity	
	Climate Dissimilarity (Over Time)	
	Climate Stability	
	Climatic Isolation	
	Climatic MoistureIndex (CMI)	
	Heat Moisture Index	
	Current Climate Diversity	
Climate- Water Balance		
	Actual Evapotranspiration (AET)	Ackerley et al. 2020
	Climatic Water Deficit (CWD)	
	Potential Evapotranspiration (PET)	
Continental position		
	Coastal Distance	Stalberg et al. 2018
	Latitude	
Drought refugia		
	Drier Climate (relative)	Cartwright et al. 2020
	Ecotones	
	Elevation	
	Soil Available Water Capacity	

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	Soil Bulk Density	
Fire		
	Fire Regime Changes	Rojas et al. 2013
Hydrology		
	Hydrology and water quantity	Rojas et al. 2013
Land Cover Extent		
	Percent Cover (e.g., Forest)	Cartright 2018; Estevo et al. 2022; Hoffrén et al. 2022
	Percent Ecotype/Area (e.g., Fir)	
	Total Basal Area (e.g., "forests")	
Land Cover Pattern/Landforms		
	Canyons	Carroll et al. 2017; Cartwright et al. 2018; Dobrowski 2011; Estevo et al. 2023; Gentili et al. 2014; Haire et al. 2022; Stalberg et al. 2018; Stark and Fridley 2022
	Catchment Area	
	Catchment Slope	
	Convergent Features	
	Distance To Ecotone (E.G. Fir)	
	Facet ID Values	
	Hilltop Present	
	Landforms	
	Presence Of Debris-Covered Glaciers, Rock Glaciers And Boulder-Streams (For Alpine)	
	Presence Of Incised Valleys	
	Proportion Headwater	
	Presence Of Ridges	
	Stream Distance	
	Topofacet Layer	
	Valley Bottoms Presence	
	Valley Bottoms Proportion	
	Valley Depth	
Land Use		
	Human Footprint	Carroll and Noss 2020; Rojas et al. 2013
	Human Use of Wildlands	
	Urban Expansion	
Soils		
	Moisture Holding Capacity	Ackerly et al. 2020;

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	Presence Of Nonsaline Alluvial Soils	Carroll et al. 2017; Cartright 2018; Duniway et al. 2021
	Soil Bulk Density	
	Soil Order	
Topography		
	Aspect	Ackerley et al. 2021; Carroll et al. 2017; Cartwright et al. 2020; Dobrowski 2011; Estevo et al. 2022; Gentili et al. 2014; Haire et al. 2022; Hoffren et al. 2023; Stalberg et al. 2018; Stark and Fridley 2022
	Elevation	
	Landform	
	Mid-Slope Position	
	North–South Corridor Potential	
	Slope	
Topographic Index		
	Annual Radiation	Ackerley et al. 2021; Carroll et al. 2017; Cartwright et al. 2020; Dobrowski 2011; Estevo et al. 2022; Gentili et al. 2014; Haire et al. 2022; Stalberg et al. 2018; Stark and Fridley 2022
	Compound Topographic Index (CTI) / Topographic Wetness Index (TPI)*	
	Daily Radiation	
	Heat Load Index (HLI)	
	Presence of North Facing Slope	
	Slope + Aspect (Southness)	
	Terrain Roughness/Terrain Roughness Index*	
	Terrain Ruggedness Index (TRI)*	
	Topographic Convergence Index	
	Topographic Position Index (TPI)*	
Topodiversity**		
	Aspect Diversity	Carroll et al. 2017; Carroll and Noss 2020; Malakoutinakhah et al. 2019
	Ecotype Diversity	
	Elevational Diversity	
	Heat Load Index (HLI) diversity	
	Land facet diversity	
	Proportion High Land Facet Diversity Represented Across Land Facet Types	
	Topographic Diversity	
Topodiversity Index		

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	Elevation + Topodiversity	Carroll et al. 2017; Carroll and Noss 2020
	Elevational and HLI Diversity	
Vegetation		
	Normalized Difference Moisture Index (NDMI)	Haire et al. 2022
	Normalized Difference Vegetation Index (NDVI)	

*Variations exist in how these are calculated. Studies also employ these at different spatial scales, which are not elaborated on here.

**Diversity metrics that include combinations of other diversity metrics are not noted here.

4. Selection of Refugia Indicators

The majority of studies that consider climate refugia for vertebrate species use species distribution models to infer patterns of habitat use and habitat stability across species. Our review of refugia indicators was almost entirely based on studies of plant communities. However, there is ample evidence for the use of these refugia indicators for wildlife. Of particular importance are metrics that relate to the influence of topography on local climates. We selected these indicators, in addition to other climate change indicators, to cover both distance and stability considerations. There were four primary criteria for selection of indicators:

1. Traceable to an interdisciplinary understanding of study system (sensu Kenney et al. 2018)
2. Coverage (New Mexico-wide)
3. Deals with one or more terrestrial habitats
4. Documented relationship to climate change or variability

Following Stalberg et al. 2018, we consider climate indicators that identify areas that include either high climatic diversity or thermally stable areas. Both have advantages and reduce the distance a species may need to move to find suitable habitat. In general, macrorefugia are represented by metrics produced from downscaled Global Climate Model (GCM)projections (Stralberg et al. 2018). Regional climate estimates (≥ 1km resolution) based on interpolated weather station data largely reflect broad-scale gradients such as those generated by latitude, continentality, and the movement of air masses (Dobrowski et al. 2011). For terrestrial species, macrorefugia are commonly inferred based on the relationship between regional climates and the distribution of species (i.e., limiting climatic factors; Dobrowski et al. 2011). However, these methods are limited because species may not always respond to large scale phenomena, and there is increasing support for the importance of microrefugia (i.e., areas to which species can retreat when regional conditions become unfavorable). Microrefugia consider the potential for local terrain patterns to moderate regionally limiting climates (Dobrowski et al. 2011).

Climate warming is occurring at different rates along latitudinal and elevation gradients. In addition, observed increases are asymmetric: minimum temperatures have increased nearly twice as rapidly as maximum temperature in the United States (Brown et al. 1992; Dettinger and Cayan 1995) and elsewhere (Beniston et al. 1994). The greater rise in minimum versus maximum temperatures highlights the importance of current and future microrefugia for supporting the minimum temperature regimes of existing climates (Dobrowski et al. 2011). Organisms that inhabit relatively warm microclimates under current conditions may use cooler microclimates to reduce the need to disperse over the long distances that might be required (as projected by macroclimate models) over the next century in order to keep pace with changing macroclimate conditions (Dobrowski et al. 2011). Ashcroft et al. (2013) state the importance of identifying factors that distinguish local refugia from apparently unfavorable conditions at coarser scales (e.g., factors that facilitate the decoupling of local and regional climates). Temperature increases will vary across microclimates (Beaumont and Hughes 2002), and species respond to spatially heterogenous regional climates instead of global averages (Walther et al. 2002). The importance of microrefugia for determining species presence can be seen in the dramatic change in plant species composition often observed along steep elevation gradients or in areas with topographically complex terrain, and studies have found evidence that local variation in climate can affect plant species' distributions (Dobrowski et al. 2011). There is also historical data that suggest that the difference between microclimate and macroclimate temperatures could increase as macroclimate temperatures warm (De Frenne et al. 2021), which could further decouple regional and local warming rates (Lenoir et al. 2017; Dobrowski et al. 2011).

Table 3. Candidate list of climate refugia indicators to be considered for inclusion in analysis of New Mexico landscapes. These data have been gathered (Available) or were derived from Elevation or Climate information (Calculated) and are currently stored in either a geodatabase or the collaborative ArcGIS Online. Supplemental File 1 describes the underlying data layers and sources. Supplemental 2 supplies the specific relationship of each metric to potential climate refugia.

Category (Metric)	Source (Available or Calculated)
Biodiversity	
1. Species Richness	Available
2. Ecosystem/Ecotypic Diversity	Available/Calculated
Climate Indices	
3. Forward Velocity	Available
4. Backward Velocity	Available
5. Presence of Climate Corridors*	Available
6. Climate Dissimilarity (over time)	Available/Calculated

7. Current Climate Diversity	Calculated
8. Climate Stability	Calculated
9. Climatic Isolation	Calculated
10. Climatic Moisture Index (CMI)	Calculated
11. Heat Moisture Index (HMI)	Calculated
Derived Climate Variables (based on current and projected temperature and precipitation variables)	
12. Aridity Index (AI)	Available
13. Climatic Water Deficit (CWD)	Available
14. Mean Annual Temperature	Calculated
15. Annual Minimum Temperature	Calculated
16. Annual Maximum Temperature	Calculated
17. Interannual Range of Temperatures	Calculated
18. Interannual Range of Precipitation	Calculated
19. Mean Annual Isothermality	Calculated
20. SWE April	Calculated
21. Total Annual Precipitation	Calculated
22. Total Precipitation Warmest Quarter	Calculated
23. Potential Evapotranspiration (PET)	Calculated
24. Actual Evapotranspiration (AET)	Calculated
25. Summer Vaper Pressure Deficit (VPD)	Calculated
26. Spring AET	Calculated
27. Summer AET	Calculated
28. Spring PET	Calculated
29. Summer PET	Calculated
30. Mean Dry Degree Days	Available
Future Change	
31. Magnitude Change Mean Annual Temperature	Calculated
32. Magnitude Change Summer Maximum Temperature	Calculated
33. Magnitude Change in Winter Minimum Temperature	Calculated
34. Percent of Normal Future Annual Precipitation	Calculated
35. Percent of Normal Future Winter Precipitation	Calculated
36. Percent of Normal Future Spring Precipitation	Calculated
37. Percent of Normal Future Summer Precipitation	Calculated
Topography	
38. Elevation	Calculated
39. Slope	Calculated
40. Ruggedness	Calculated
41. Aspect (radians)	Calculated
42. Aspect (linear)	Calculated
Derived Topographic	
43. Landform	Calculated
44. Catchment Area	Calculated
45. Curve	Calculated

46. Mean Elevation	Calculated
Topographic Indices	
47. Heat Load Index (HLI)	Available
48. Terrain Ruggedness Index (TRI)	Calculated
49. Northness (cosine of aspect in radians)	Calculated
50. Eastness (sine of aspect in radian)	Calculated
51. Topographic Position Index (TPI)*	Calculated
52. Compound Topographic Index (CTI)/Topographic Wetness Index (TWI)	Available/Calculated
53. Slope + Aspect (Southness)	Calculated
54. Topographic Convergence Index	Calculated
55. Vector Ruggedness Index	Calculated
56. Standard Deviation of Slope	Calculated
Land Cover Pattern/Landforms	
57. Topofacet Layer	Available
58. Facet ID values	Available
59. Convergent Features (e.g., catchments, valleys, headwaters, canyons)	Calculated
60. Presence of Ecotones	Calculated
61. Distance to Ecotone (e.g., Fir)	Calculated
62. Percent Cover (e.g., Forest)	Calculated
63. Stream Distance	Calculated
Topographic Diversity	
64. Aspect Diversity	Calculated
65. Elevational Diversity	Calculated
66. HLI diversity	Calculated
67. Land Facet Diversity	Calculated
68. Topographic Diversity	Calculated
Soils	
69. Percent Soil Bulk Density, 1m	Available/Calculated
70. Soil Water Storage/Available Water Capacity	Available
71. Available Soil Moisture	Available/Calculated
72. Mean Duration Dry Soil Intervals	Available
73. Presence of Shallow or Finer Textured Soils	Available/Calculated
*Climate corridors are areas that form the best route between current or future climate types.	

Several features have been identified as cold microrefugia that might be important in arid environments that exist within New Mexico: north-facing slopes, cold-air drainages, local topographic concavity (features that lead to less exposure to hot winds and radiation, higher soil moisture), canopy density (thermal buffering and moisture retention), and higher elevations (temperature and precipitation gradients) (Dobrowski 2011; Kennedy 1997; Lenoir, Hattab, and Pierre 2017; Noss 2001; Bennett and Provan 2008; Ashcroft et al. 2009, 2010; Fridley 2009). Analysis of microrefugia also requires an understanding of larger regional scale patterns in climate change (Dobrowski et al. 2011). For instance, seasonal changes in climate, which are considered coarse-scale measures of refugia potential, are influenced at the local scale by factors that may have different outcomes depending on the species. In general, sites that are able to maintain more moisture (e.g., due to topographic or soil characteristics) are considered better able to buffer climate changes, particularly increased heat, and are therefore identified as having high potential to constitute microrefugia. However, sites that can maintain dry conditions throughout the winter months (e.g., by good drainage, high solar exposure, sandy soils) may also maintain higher than average temperatures during the winter months, which could be important for maintaining populations of ectothermic animals such as insects during colder seasons (Ashcroft and Gollan 2013). Best practices for identifying refugia include considering a diverse set of biotic data and fine- and coarse-scale measures that are able to capture a range of potential variability and species dynamics (Ashcroft and Gollan 2013).

After our initial review of the literature, we noted several studies that also include measures of habitat resilience such as the presence of non-climate disturbances. These measures were considered indicative of site potential for providing refugia and have been collected in addition to the more typical indicators based on climate and topography. Similarly, we found that studies commonly assess a metric's importance through its relationship to biodiversity or specific species presence. Biodiversity indicators represent the biological potential of an area for recovery (via metapopulation dynamics) and colonization.

Themes of Refugia

We categorize the metrics listed in Table 3 under several themes, which are discussed briefly below. Supplemental 1 and 2 also provide further background and justification for inclusion of specific metrics listed in Table 3.

Biodiversity

A primary goal of delineating climate refugia is to identify areas that may help us mitigate the impact of anthropogenic climate change on biodiversity (Hoffrén et al. 2022). Thus, most studies of climate refugia include an analysis that ranks refugia based on the characteristics of areas with high biodiversity. Biodiversity is also an innate indicator of refugia because biodiversity can represent the biological potential of an area to experience population recovery (via metapopulation dynamics and colonization). Later discussions of climatic and topographic diversity relate closely to this principle because these landscape-level indicators are used primarily due to their expected representation of biodiversity. For example, Carroll et al. 2017 use land facets as a coarse-filter surrogate for biodiversity and argue that land facets can augment biodiversity data in conservation planning processes.

Climate

The most obvious set of climate refugia indicators will relate to measures of climate change. In the context of climate refugia, these metrics can be considered one of two ways: 1) The absolute change in conditions and 2) The rate at which change occurs. Absolute change might be reduced for some areas or simply not exceed the tolerances of occupying species. Rate of change influences how well species might be able to adapt to conditions and how far they will have to travel to find areas that match current conditions in the future. In terms of identifying refugia, these considerations are often summarized through estimations of local climate stability and the proximity of suitable conditions under future warming. At the level of microrefugia, stability is defined as a relatively low degree of change in temperature or precipitation regimes. At a microrefugia level, stability might arise due to features that buffer regional changes. The rate at which climate will change corresponds to the distance that a species must travel to track suitable conditions.

Climate indicators and metrics are broken into three main categories: 1) Derived climate variables estimate current conditions at sites to allow for a comparison of what types of change are likely across a landscape; 2) Historic and future change, which provide a basis for assessing the relative stability of a site in terms of the magnitude of climate change impact; 3) Climate indices, which measure aspects of climate change relating to both climate stability and potential climate buffering. Climate changes indices are oriented towards estimating the impact of change from the perspective of species.

Derived Climate Variables (based on current and projected temperature and precipitation variables) and Future Change

Several metrics included in this analysis represent existing climate conditions or expected changes at the regional scale. These metrics are used to compare relatively larger-scale trends in climate variations and capture seasonal trends not addressed in other derived metrics. Trends in climate change, either over historic periods or as estimated from future projections, can be used to identify potential areas of climate stability (Ashcroft 2010). Under this principle, historically-observed changes or future changes are used to identify refugial capacity, with areas of less and slower change considered to better represent potential refugia (Rojas et al. 2021). Thermally stable areas will also provide refuge due to a realized lower sensitivity to extreme events (Hoffrén et al. 2022). For instance, it has been documented that the diurnal ranges of both soil and air temperatures are reduced and the role of elevation in meditating the spatial distribution of temperatures is greater under moist conditions (Ashcroft and Gollan 2013). Therefore, areas with greater moisture availability might be considered more likely to constitute climate refugia.

Seasonal variation in climatic conditions is important to consider not only from the perspective of phenology (heavily emphasized in the literature on climate change indicators) but also with respect to variations among species in terms of limiting conditions. Ashcroft (2013) notes that species distributions are commonly modeled based on a specific subset of climate variables: mean annual temperature, winter minimum, and either summer maximum or an estimate of growing degree-days and, “While these variables have been selected based on the general physiological response of species, this *a priori* selection of predictors will lead to erroneous predictions for species that are limited by temperatures during other seasons.” Namely, seasonal rates of warming vary, and, in many areas, minimum temperatures have increased more than maximum and average temperatures (Loehle and LeBlanc 1996). Studies have found that models including seasonal fine-tuning of climatic variables perform better (Heikkinen et al. 2006). In their assessment of climate change indicators, Weltzin et al. (2020) strongly advocate for the inclusion of seasonal climate indicators. However, though likely important, the ecological impacts of increased climate variability that might be inferred through seasonal estimates are poorly understood (Adler et al. 2006) and we do not yet know whether such measures will relate to our proxy measures of potential refugia (e.g. species richness, climate stability).

Climate Indices

Climate Indices are used here to represent a series of derived climate characteristics that either represent more advanced considerations of water balance within an ecosystem (e.g., temperature-based estimates of moisture as seen with the Climate Water Deficit) or that represent relative capacity within a landscape to provide climatically suitable areas in the future. Within the latter group are metrics that rank the landscape based on estimated proximity of similar climates under future conditions. Climate velocity estimates the distance between current and future analogous climates, whereas climate isolation/dissimilarity metrics are meant to represent the likelihood of finding similar conditions under future scenarios at a given location. Climatic diversity follows the logic of other diversity metrics in which areas of high diversity represent potential refugia because these areas are likely to reduce the distance a species has to move in order to find climatically suitable conditions (Hoffrén et al. 2022).

Topography (*Derived Topographic/Topographic Indices/Topographic Diversity)*

The relationship between species distributions, communities, ecosystems, and overall biodiversity to abiotic drivers such as soils, geology, and topography are well documented (Stein, Gerstner, and Kreft 2014). The use of topographic and vegetation factors in analysis of climate refugia is based on the capacity of these factors to buffer areas from climate change by reducing exposure to extreme temperatures and external fluctuations (Hoffrén et al. 2022). A key aspect of topographically-related indicators of refugia is that they have characteristics that decouple regional from local climates. Because global climate models cannot be used to estimate local climate phenomenon, studies must rely on topographic features to serve as surrogates. In addition, site characteristics such as the presence of vegetation and soil type influence the degree to which local conditions change. Important mechanisms for buffered sites are characteristics that reduce net radiation fluxes, such as greater canopy cover or topographic features that promote cold air pools or create shelters from wind (Ashcroft et al. 2009; Ashcroft and Gollan 2013; Dobrowski 2011; but see also Ashcroft et al. 2012 for evidence that cold air pools actually have higher climatic variability). Several topographic features have been determined to be associated with cold microrefugia: north-facing slopes and cold-air drainages (Dobrowski 2011) and local topographic concavity. These areas will favor the persistence of certain organisms and can also introduce local diversification into the regional matrix of temperatures and moisture (Hoffrén et al. 2022). In their meta-analysis of 192 studies, Stein, Gerstner, and Kreft (2014) found particularly strong associations between species richness and vegetation and topographic heterogeneity. Unlike vegetation and species, topographical features will not change over the next century as climatic conditions change. Therefore, these features provide a predictable aspect of the landscape to use in identifying refugia.

Topographic diversity (topodiversity) has been studied extensively in the literature as a potential buffer against future climate change, but there is still considerable discussion around how topographic complexity functions and should be measured (Dobrowski 2011; Ackerly et al. 2010; Ashcroft 2010; Ashcroft et al. 2012; Keppel and Wardell-Johnson 2012). From the perspective of species, areas with higher topographic diversity can represent areas where heterogeneity in the physical environment (e.g., steep elevation gradients or diverse aspects) increases the likelihood that species will be able to find suitable habitat proximate to their current location as climate conditions change (Carrol 2017).

Land Cover Pattern / Landforms

Related to topography, landforms have been used in several studies to identify climate microrefugia. Ashcroft and Gollan (2013) argue that sites with the greatest resilience to climate change are those that are more likely to remain moist because such sites can absorb the same amount of radiation as drier sites and experience less resulting change in local temperatures. This includes features such as sheltered gorges, forests, or coastal and high elevation sites. Although the latter represent larger scale features, others have also pointed to the importance of plant cover for buffering climate changes (Hoffrén et al. 2022).

Percent natural cover has been used as a metric of refugia in terms of habitat resilience (Rojas et al. 2021). Percent forest cover and proximity to certain ecosystem types has been used to infer climatically-buffered zones or areas that might provide more limited responses to other land change phenomena (e.g., beetle-related mortality in forested ecosystems; Cartwright et al. 2018).

Soils

The relationship between species distributions, communities, ecosystems, and overall biodiversity and abiotic drivers such as soils, geology, and topography are well documented (Stein, Gerstner, and Kreft 2014). Several analyses of climate and drought refugia have included soil characteristics as significant predictive factors (Carroll et al. 2017; Cartwright 2018; Ackerly et al., 2020; Duniway et al., 2021). Thermal inertia of moist soils can buffer surface temperature changes (Ashcroft and Gollan 2013), which points to the importance of several soil characteristics in identifying climate (and drought) refugia. Soil moisture, a potentially important buffering agent for soil temperature change, is determined by Vapor Pressure Deficit, topographic position, and soil texture (Ashcroft et al. 2013)

Land Use

Although not listed in Table 3, land use and other measures of disturbance are likely important to include in an analysis to identify refugia. The presence of characteristics representing stable conditions (e.g., topography) is only one facet of what constitutes usable habitat for wildlife. Changing disturbance regimes are recognized as an important consequence of climate change in forest ecosystems. In addition to identifying climate refugia, there is a simultaneous need to locate and investigate possible refugia from disturbances such as drought and fire (Cartwright 2018). Anthropogenic features that modify hydrologic flows are known to affect the ability of watersheds to sustain functional habitats (Rojas et al. 2021). Recreational activities may alter the refugial capacity of ecosystems and affect the ability of the landscape to sustain species and their habitats (Larson et al. 2016; Rojas et al. 2021). Increased fire frequency is also a primary threat because it can degrade and convert natural communities (Rojas et al. 2021). Rojas et al. (2018) devised a framework to quantify and visualize areas that have low exposure to multiple stressors, which they associate with higher refugial capacity. These areas are more likely to facilitate the persistence of species, populations, or communities in future landscapes. In addition, they used their criteria to identify “super refugia” that can be targets of limited conservation resources. Rojas et al. (2018) acknowledge that the concept of stressors relates more to the assessment of ecosystem risk for negative impacts resulting from disturbances. However, given the potential for changing climatic conditions to create novel ecosystems and climates and for climate change impacts to interact with disturbance, it may be prudent to consider non-climate stressors in order to better capture the dynamic landscape features that influence refugial capacity.

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5. Data

I. Data Master List

A complete description of primary data is found in Supplemental 1: Data Catalogue. Supplemental 2 contains a list of the definitions and calculations for refugia indicators that we will use for the first round of analysis.

II. Methods for Data Processing (Supplemental File 1)

Most data are summarized for three spatial extents: Ecoregion, Hydrological Unit Code 12 (HUC12) watershed, and the Crucial Habitat Assessment Tool (CHAT). We also explored patterns for existing Conservation Opportunity Areas (COAs). Several workflows were developed for individual datasets and are available upon request. For continuous data, we calculated the mean for each area of interest. For discrete data, we calculated percent area of each class within each area of interest. We used either Shannon diversity or Simpson diversity indices to create topodiversity metrics across New Mexico and for each unit of analysis. Climate data and climate-derived variables were downloaded for CMI Phase5 General Circulation Models (GCM)s under a scenario defined by Representative Concentration Pathway 4.5. For the most part, we focused on midcentury values (2040-2060 or "2050"). To maintain consistency among different datasets, we based all our calculations on an ensemble of the 15-17 models available for this time period and scenario. We also downloaded and stored CMIP6 projections but have not yet processed these files.

III. ArcGIS Online (AGOL)

We initiated an online ArcGIS collaborative space to share data and solicit feedback on analyses. Access to the AGOL can be granted upon request.

6. Analysis

As mentioned above, we summarized most variables by 4 spatial extents: Ecoregion, HUC12, COA, and CHAT (Figure 1). CHAT-level summation may not be suitable for some data that were produced at larger spatial scales. We also conducted a preliminary analysis of indicators for COAs to identify how climate-specific indicators compare within COAs as well as among COAs as compared to non-COA areas. Processing steps are included in metadata and workflows can be shared upon request.

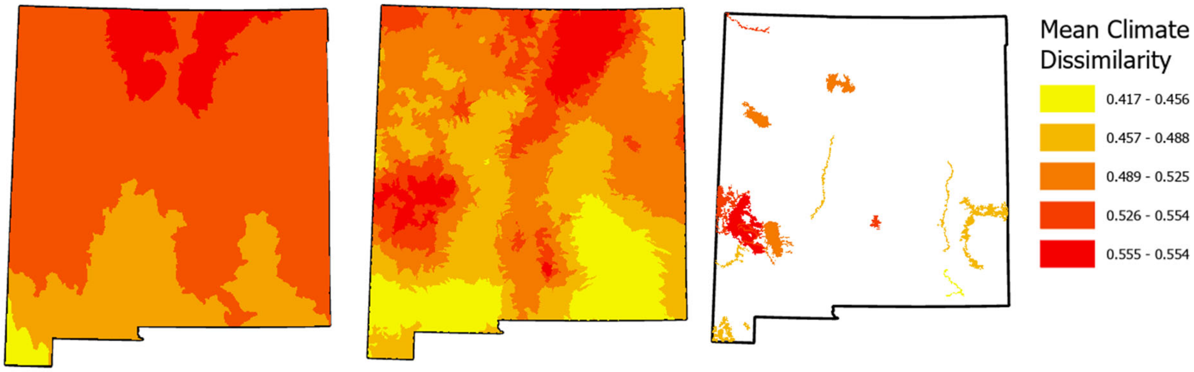

Figure 1. Climate dissimilarity (CD) is a multidimensional measure of climate exposure that represents how different future climates will be from current conditions. This measure can capture the influence of not only absolute change but seasonality of changes in temperature and precipitation. Here, CD is shown summarized by Ecoregion, HUC12, and by Conservation Opportunity Area boundaries. Data provided by [AdaptWest.]()

7. Results

Here we briefly examine how well current COAs represent or contain conditions known to be associated with the presence of macro- and microrefugia. COAs are areas that, under current climatic conditions, are considered to have superior potential for conserving SGCN (https://nmswap.org/conservation-opportunity-areas). On average the climate metrics summarized for COA are closer to conditions associated with climate refugia when compared to the entire state (**Table 4**). Climate dissimilarity and velocity metrics are lower on average within

COAs, indicating relatively stable conditions. Absolute change in temperature is also reduced in COAs versus the entire state and COAs are likely to experience less drastic changes in annual patterns of precipitation.

Climate dissimilarity values are similar across most COAs, but considerable variation exists in estimates of backward velocity among COAs (**Figure 3**). The Lower Pecos and Black Rivers and Middle Rio Grande COAs have strikingly higher values for backward velocity, indicating relatively less potential for these COAs to serve as climate change refugia. These areas are also expected to see reductions in mean annual precipitation, though similar declines in precipitation are seen for other COA as well (**Figure 4**). The Lower Pecos and Black River, Middle Pecos River and northern Sacramento COA experience the greatest declines in mean annual precipitation (10, 9.25, and 7% less than observed average, respectively) and the Middle Rio Grande, Lower Pecos and Black River, and Gila River Headwaters COA experience the greatest expected increase in mean annual temperatures (2.72, 2.58, 2.54 °C, respectively).

Table 4. Comparison of climate metrics for Conservation Opportunity Areas (COAs) vs. the entire state of New Mexico, based on projected changes in temperature and precipitation to 2050 (2040-2060) under an averaged ensemble of 15 General Circulation Models generated in the Coupled Model Intercomparison Project Phase 5 using Representative Concentration Pathway 4.5.

	Entire State	**Average across all COAs**
Climate Dissimilarity	0.41 to 0.68	0.41 to 0.55
Forward Velocity	0 to 6.39	0.39 to 3.3
Backward Velocity	0 to 9.26	0.45 to 4.6
Change Mean Annual Temp (C)	-1 to +5	+1.6 to2.7
Change Annual Max Temp (C)	-2 to +7	+2 to 5
Percent Change Annual Precipitation	+38 to -57%	+2 to -10%
Percent Change Annual Precipitation Wettest Month	+40 to -56%	+12 to -19%
Percent Change Annual Precipitation Driest Month	+119 to -79%	+1 to -26%
Precipitation Seasonality	+17 to -24	+6 to -3.4

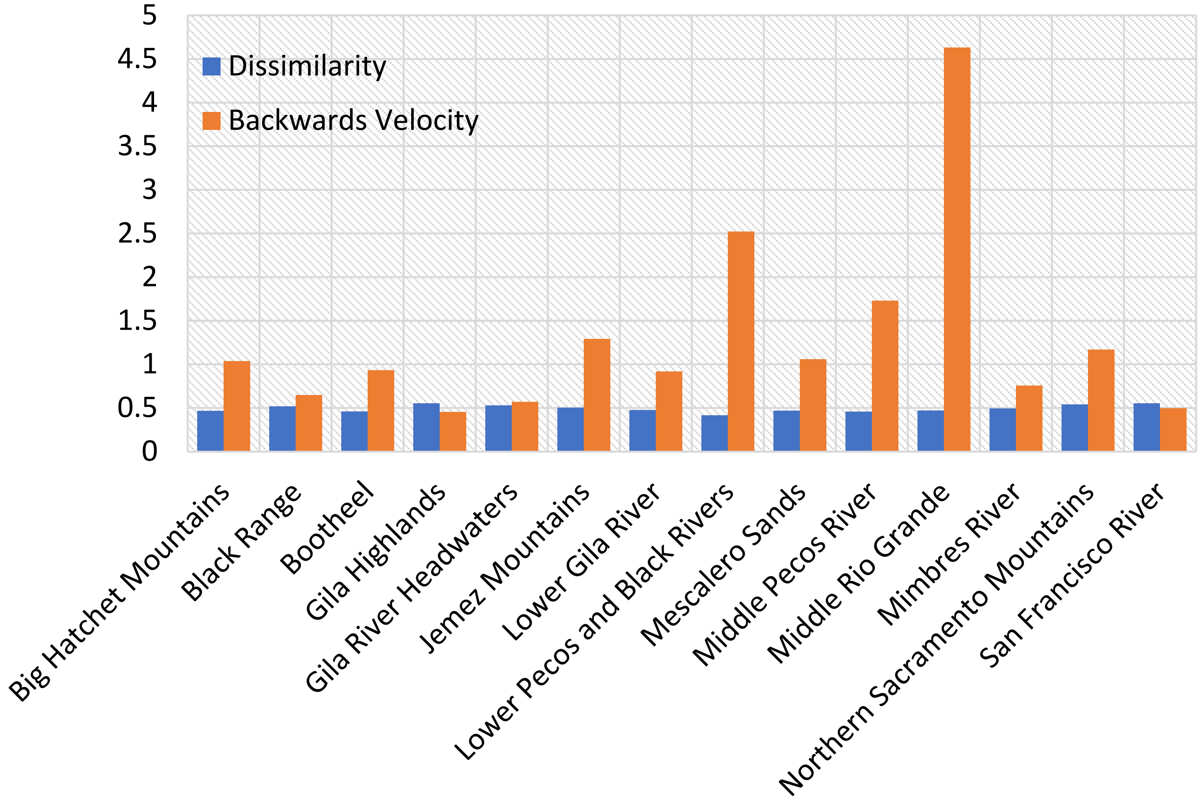

Figure 2. Average of climate metrics for 14 Conservation Opportunity Areas (COAs). Climate dissimilarity (CD) is a multidimensional measure of climate exposure that represents how different future climates will be from current climates. Backward velocity estimates the distance from a current area where similar climates can be found in the future. Lower values mean less distance between current and future sites, and are considered indicative of an area's potential to constitute a climate refugia (Data obtained and summarized from the AdaptWest project).

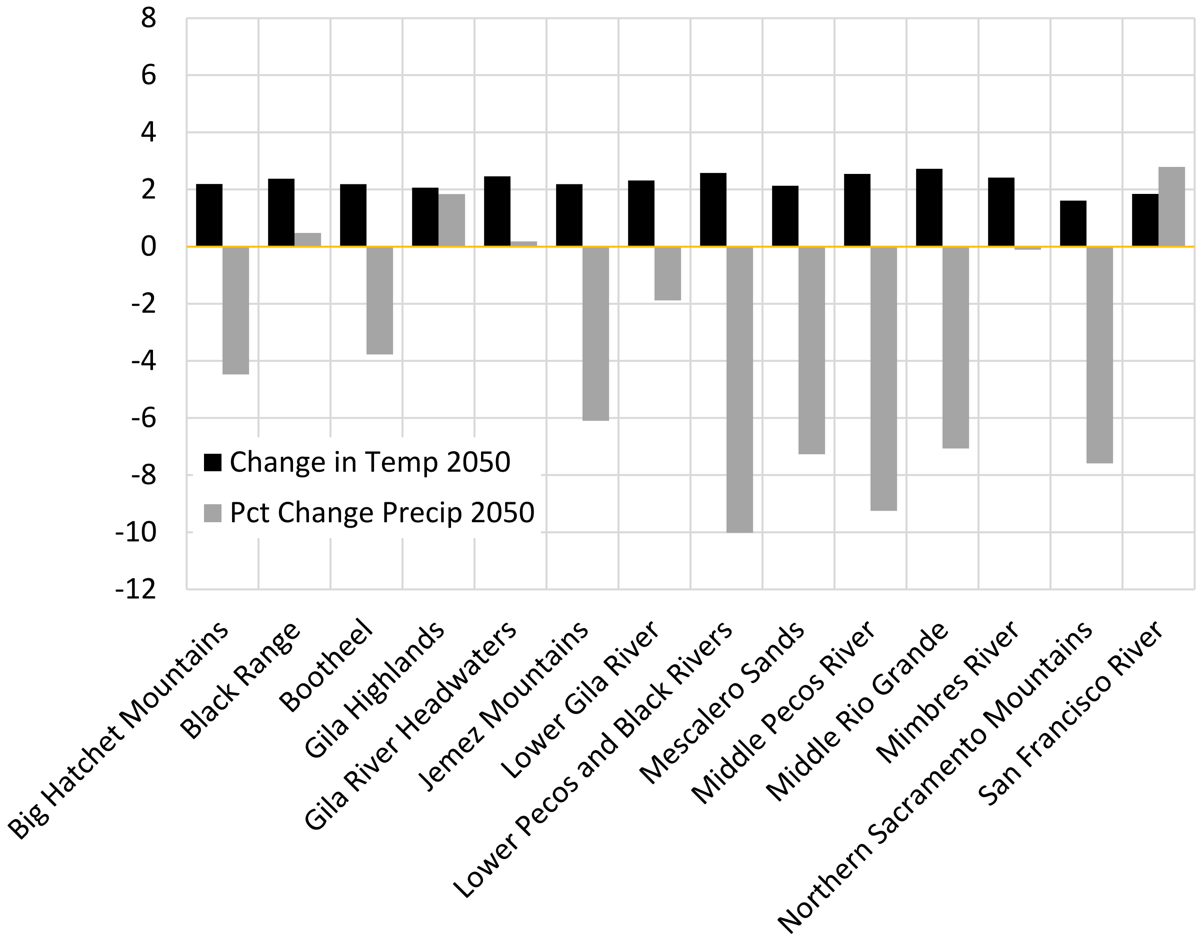

Figure 3. Absolute change in mean annual temperature (C) and percent change in annual precipitation (mm) for 14 Conservation Opportunity Areas (COAs) in New Mexico under Representative Concentration Pathway 4.5. Values are based on an ensemble of 17 General Circulation Models generated in the Coupled Model Intercomparison Project Phase 5 General Circulation Models. Data obtained and summarized from WorldCLIM site.

8. Next Steps (year 2 activities)

1. Summarize findings in models of species distributions that might have relevance to the identification of climate change refugia.
2. Continue to develop and assess spatial data that can be used to identify climate refugia. We will use species richness and other factors identified by NMDGF staff to represent conservation value and then formally analyze the relationship between indicators of climate refugia and species presence to develop a ranking system for the final selected indicators.
3. Analysis of ideal spatial resolution for identified climate- and topographic-related climate change indicators (e.g., at which scale are the metrics doing the best job of predicting areas of high biodiversity).
4. Begin to develop composite layers from individual refugia indicators to identify climate refugia using methods identified in literature and Zonation software.
5. Upload data to AGOL. Create better interface for collaboration.
6. Synthesize and integrate information for aquatic ecosystems.