Appendix A

Identifying and mapping climatically stable macro- and micro-refugia in New Mexico

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Year 1 Final Report, May 2024

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Year 1 Final Report

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Compiled by Megan Friggens and Karen Cooper

Table of Contents

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.

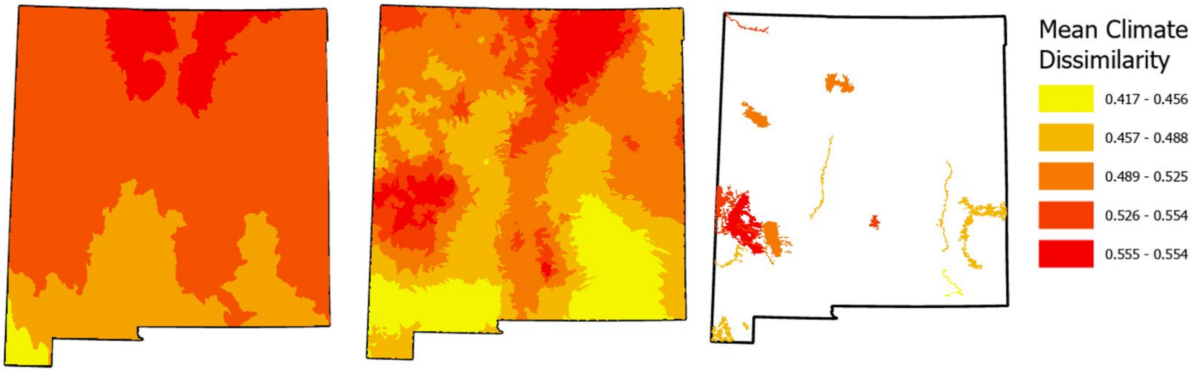

Figure 1. Climate dissimilarity (CD) is a multidimensional measure of climate exposure that represents how different future climates will be from current conditions. This measure can capture the influence of not only absolute change but seasonality of changes in temperature and precipitation. Here, CD 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

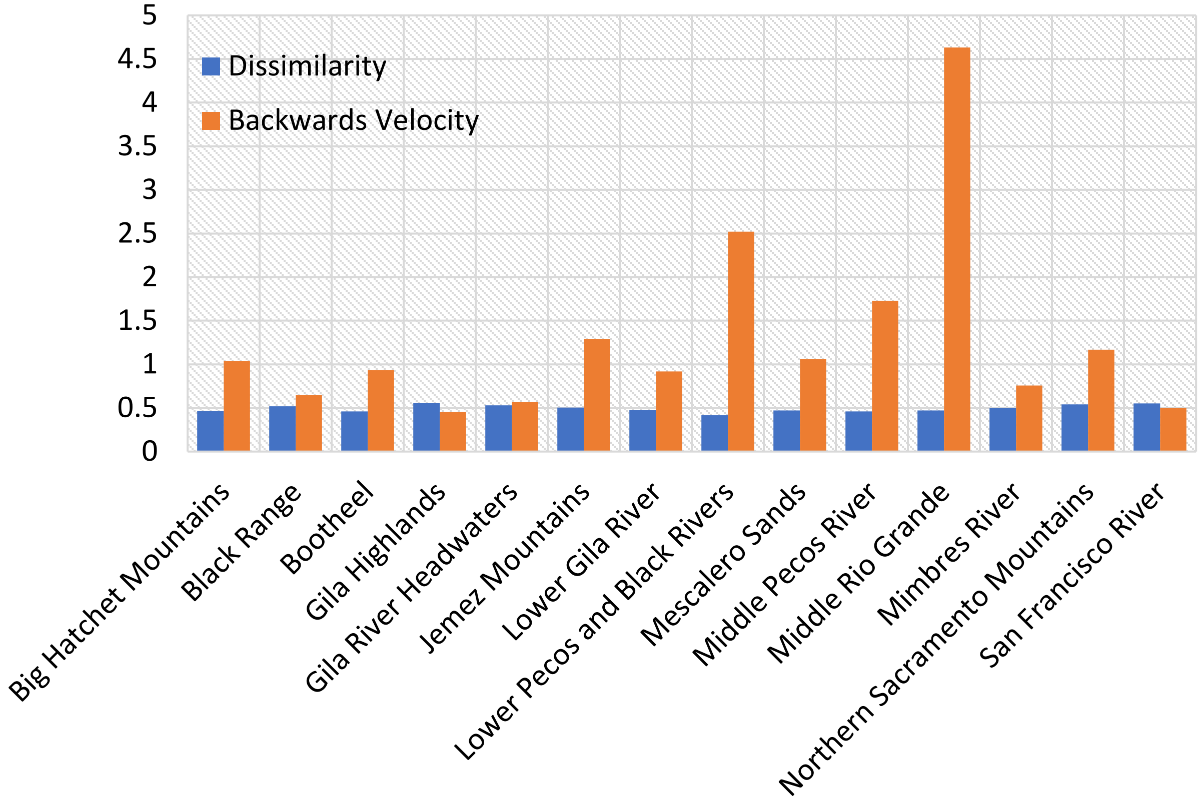

Figure 2. Average of climate metrics for 14 Conservation Opportunity Areas (COAs). Climate dissimilarity (CD) is a multidimensional measure of climate exposure that represents how different future climates will be from current climates. Backward velocity estimates the distance from a current area where 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).

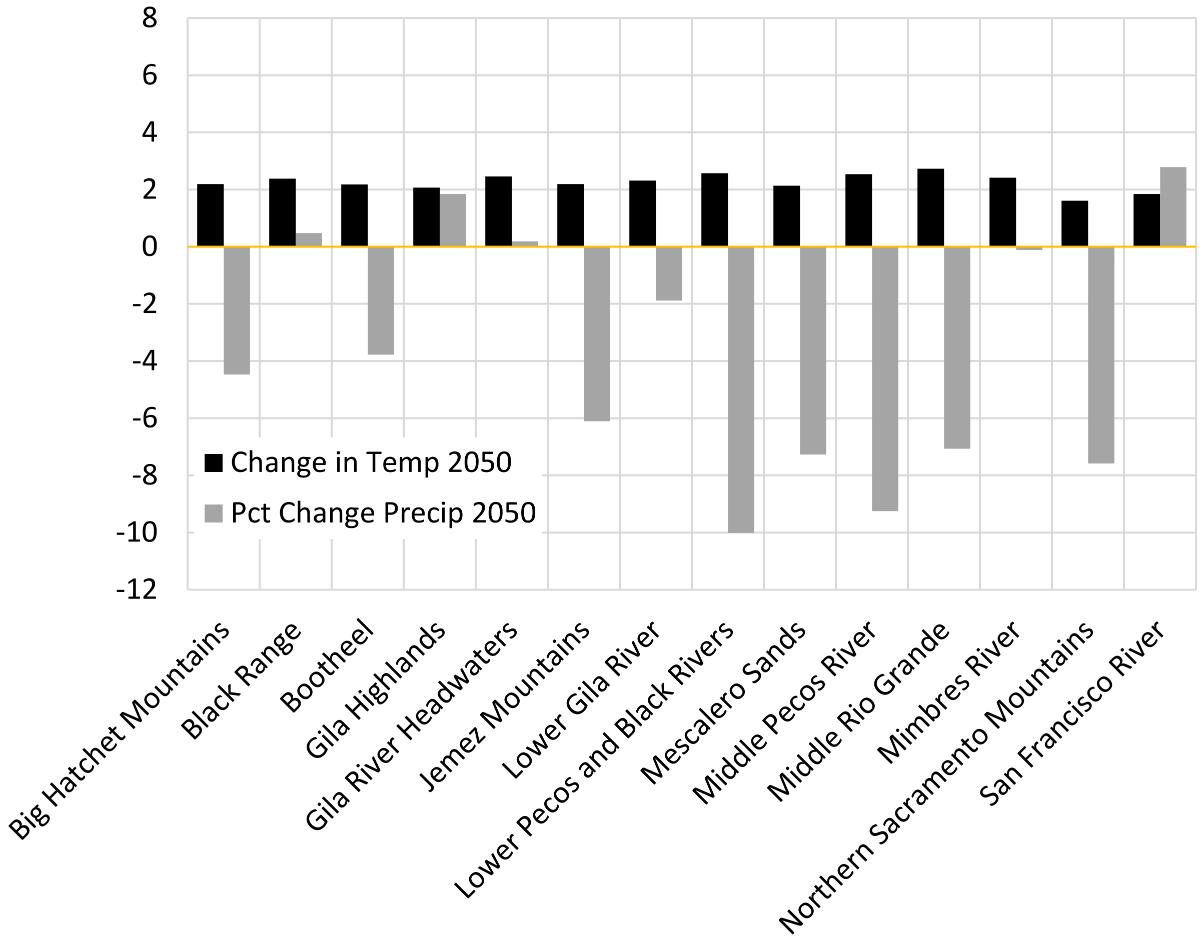

Figure 3. Absolute change in mean annual temperature (C) and percent change in annual precipitation (mm) for 14 Conservation Opportunity Areas (COAs) in New Mexico under Representative Concentration Pathway 4.5. Values are based on an ensemble of 17 General Circulation Models generated in the Coupled 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.

IDENTIFYING AND MAPPING CLIMATICALLY STABLE MACRO- AND MICRO-REFUGIA IN NEW MEXICO: Supplemental 1. Data Catalogue

Agreement Number 23-CO-11221632-013

Year 1 Report, 2 of 3.

The following 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. This is a working document and will be updated as work progresses. Asterisks indicates it is an active file within current analysis. Last update 5/1/2024.

Compiled by Megan M. Friggens and Karen C. Cooper as part of agreement #23-CO-11221632-013 to accompany spatial data products and associated project ArcGIS Online Map.

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Table of Contents

Terrestrial

1. Rehfeldt Vegetation Projection

Source: Databasin.org, RMRS Moscow Lab
Link: Biome Climatic Niche Vegetation Model | Data Basin
Reference:

- Rehfeldt, G. E., N. L. Crookston, C. Sàenz-Romero, and E. M. Campbell. 2012. North American vegetation model for land-use planning in a changing climate: a solution to large classification problems. *Ecological Applications*, 22, pp. 119-141.

Description: The model uses Random Forests classification trees to predict the response of a biome to projected climate change. The climatic niche vegetation model defines the climatic conditions in the current distribution of a vegetation type and forecasts locations on the landscape where similar conditions are expected to occur under different climate scenarios.
Justification: As climate conditions change, climatically static vegetation models may not be suitable to deal with the variability of climate-driven ecosystem change. Climate-driven vegetation models help reduce uncertainty when planning for land management in a changing environment (Rehfeldt et al. 2012). These data may be used to identify the percent loss or gain of certain vegetation communities across New Mexico. Alternatively, this dataset may provide information on non-analogous conditions.
Data compilation: Available but not yet processed. It is not clear if this data will provide information that is not already represented in calculations of climate velocity and magnitude change.

2. Riparian Corridor

Source: Natural Heritage New Mexico, NMRipMap
Link: New Mexico Riparian Habitat Map | Natural Heritage New Mexico (unm.edu)
Reference:

- Muldavin, E., E. Milford, J. Leonard, J. Triepke, L. Elliot, P. Hanberry, D. Diamond, C. Reasner, Y. Chauvin, A. Urbanovsky, and J. Smith. 2020. New Mexico Riparian Habitat Map NMRipMap. Natural Heritage New Mexico at the University of New Mexico, U.S. Forest Service (USFS) Region 3, Missouri Resource Assessment Partnership (MoRAP) at the University of Missouri, and Geospatial Technology and Applications Center (GTAC) of the USFS, Salt Lake City, UT.

Description: The New Mexico Riparian Habitat Map (NMRipMap) version 2.0 was produced using the National Hydrology Dataset (NHD), the USFS Riparian Buffer Delineation Model V3.0 (Abood and Maclean 2012), soils maps from the Natural Resources Conservation Service (NRCS; 2017) and USFS, digital elevation models (10-m DEMs), and aerial photo interpretation. It is a fine-scaled spatial map that includes the cover, composition, and structure of riparian vegetation along perennial streams and rivers of New Mexico.
Justification: Riparian vegetation in the southwest occupies less than 0.5% of the landscape (Strong and Bock 1990). The climatic regime of the region with pulse and drought hydroclimatic seasons results in perennial streams and rivers (Webb and Leake 2006). These riparian habitats

are of critical ecological and economic importance, far outweighing their relatively modest representation in the landscape.
Data compilation: Available but not yet processed.

3. Land Use and Land Cover

Source: U.S. Geological Survey (USGS) Gap Analysis Project (GAP)
Link: Introduction to the Land Cover Viewer | U.S. Geological Survey (usgs.gov)
Reference:

- U.S. Geological Survey Gap Analysis Project, 20160513, GAP/LANDFIRE National Terrestrial Ecosystems 2011: U.S. Geological Survey, https://doi.org/10.5066/F7ZS2TM0.

Description: The GAP/LANDFIRE National Terrestrial Ecosystems data provides detailed information on the vegetation and land-use patterns if the United States. The dataset combines detailed landcover data generated by the GAP with LANDFIRE data. LANDFIRE is an interagency vegetation, fire, and fuel characteristic mapping program (http://www.landfire.gov/). The dataset combines the Ecological System classification system developed by NatureServe, representing natural and semi-natural vegetation.
Justification: The Ecological System classification data provides information on the vegetation communities that is not available in most other regional or national products (Gergely and McKerrow 2016). These data have been used to build predictive models of wildlife distribution across the landscape and identify possible habitat corridors. For this analysis, these data might contribute to estimates of landscape diversity.
Data compilation: Available but not yet processed. Processing is pending discussion and analysis of existing species distribution models.

4. Landcover

Source: USGS
Link: National Land Cover Database | U.S. Geological Survey (usgs.gov)
References:

- Homer, C., J. Dewitz, S. Jin, G. Xian, C. Costello, P. Danielson, L. Gass, M. Funk, J. Wickham, S. Stehman, and R. Auch. 2020. Conterminous United States land cover change patterns 2001–2016 from the 2016 National Land Cover Database. *ISPRS Journal of Photogrammetry and Remote Sensing*, 162, pp. 184-199.
- Wickham, J., S. V. Stehman, D. G. Sorenson, L. Gass, and J. A. Dewitz. 2023. Thematic accuracy assessment of the NLCD 2019 land cover for the conterminous United States. *GIScience & Remote Sensing*, 60(1), 2181143.

Description: The National Land Cover Database (NLCD; Version 09-20-2000) is a cooperative project between the USGS and U.S. Environmental Protection Agency (EPA). Landcover data is based on 30m Landsat Thematic Mapper (TM) data acquired from the Multi-Resolution Land Characterization (MRLC) Consortium. NLCD provides nationwide data on land cover and landcover changes across nine epochs from 2001 to 2021. Products include landcover,

landcover change index, urban imperviousness, and disturbance metrics for landcover and forests.
Justification: NLCD is a widely used dataset that allows for an analysis of current landcover and landcover from the past 20 years. For our analysis of climate change refugia, these data might contribute to estimates of landscape diversity and/or potential threats.
Data compilation: Available but not yet processed. Use is pending discussion with collaborators on the role of disturbance and land use in the current analysis. Current landcover analysis included variables derived from LandFire datasets (see Vegetation Layers #3).

5. Hydrology

Derived Data Layer:

A. Distance to Stream/water body

Source: National Hydrology Dataset, USGS
Link: **National Hydrography Dataset | U.S. Geological Survey (usgs.gov)**
References:

- Terziotti, S. and C. A. Archuleta. 2020. Elevation-derived hydrography acquisition specifications (No. 11-B11). U.S. Geological Survey. 74 pp.
- Moore, R. B., L. D. McKay, A. H. Rea, T. R. Bondelid, C. V. Price, T. G. Dewald, and C. M. Johnston. 2019. User's guide for the national hydrography dataset plus (NHDPlus) high resolution (No. 2019-1096). U.S. Geological Survey. 66 pp.

Description: The National Hydrology Dataset (NHD) represents the water drainage network of the United States at a 1:24,000 or larger scale. Features within the NHD include rivers, streams, canals, lakes, ponds, coastlines, dams, and stream gages.
Justification: Distance to water is often a primary indicator of species presence. Within the climate change literature, areas with streams show reduced temperature fluctuations and less dramatic extreme temperatures, which demonstrates the importance of these areas for providing locally buffered refugia. Presence of water was also shown to reduce bird population declines under increasing temperatures in the Mojave Desert (Iknayan and Beissinger 2018).
Data compilation: Data is available in geodatabase. We will use the Buffer tool in ArcGIS Pro to create a series of data that represent 10m, 100m, and 1000km buffer zones for inclusion in regression analysis and Zonation prioritization.

6. Watershed Boundaries*

Source: National Hydrology dataset, USGS
Link: **Watershed Boundary Dataset | U.S. Geological Survey (usgs.gov)**
Reference:

- Jones, K. A., L. S. Niknami, S. G. Buto, and D. Decker. 2022. Federal standards and procedures for the national Watershed Boundary Dataset (WBD): Chapter 3 of Section A, Federal Standards, Book 11, Collection and delineation of spatial data (No. 11-A3). U.S. Geological Survey.

Description: A companion to the NHD is the Watershed Boundary Dataset (WBD), a seamless national hydrological unit dataset. Hydrological units represent the area of the landscape that drains into a section of a stream network. Boundaries of these units are determined solely on hydrological principles, not administrative boundaries. The result is a baseline drainage boundary framework for all land and surface areas.
Justification: The hydrological units in the WBD provide a uniform method for organizing, collecting, managing, and reporting hydrologic and terrestrial information. This data provides the resolution required to locate specific hydrological environments and summarize metric information across landscapes. Several analyses and datasets use the HUC12 subwatershed boundary as a unit of analysis.
Data compilation: Data were downloaded from National Record Clearinghouse. A shapefile was created for New Mexico that was used to summarize climate, topography, and soils variables.

Species Data

1. Biodiversity

Source: NatureServe, EnviroAtlas (see list under Other)
Link: **Map of Biodiversity Importance | NatureServe**
References:

- Hamilton, H., R. L. Smyth, B. E. Young, T. G. Howard, C. Tracey, S. Breyer, D. R. Cameron, A. Chazal, A. K. Conley, C. Frye, and C. Schloss. 2022. Increasing taxonomic diversity and spatial resolution clarifies opportunities for protecting US imperiled species. *Ecological Applications*, 32(3), p. e2534.
- Pickard, B. R., J. Daniel, M. Mehaffey, L. E. Jackson, and A. Neale. 2015. EnviroAtlas: A new geospatial tool to foster ecosystem services science and resource management. *Ecosystem Services*, 14, pp. 45-55.

Description: The NatureServe Map of Biodiversity Importance is a collaboration between ESRI, the Nature Conservancy, Microsoft's AI for Earth Program, and NatureServe. Habitat models for 2,216 at-risk species in the contiguous United States were produced. Models were analyzed in combination with protected area boundaries to determine regions of high importance for the conservation of vertebrates, freshwater invertebrates, pollinators, and plants. The Map of Biodiversity Importance provides fine-scale information to help identify areas that are critical in preventing species extinctions in the U.S.
EnviroAtlas was developed collaboratively by the EPA in partnership with the USGS, the U.S. Department of Agriculture (USDA), and other federal and non-profit organizations, universities, and communities including state-, county-, and city-level stakeholders. EnviroAtlas provides data at national and community extents. The national component is summarized for the 48 mainland U.S. states by HUC 12. The community data layers are summarized by consensus block groups. There are over 400 national and community data layers. EnviroAtlas utilizes habitat models to map the number of terrestrial vertebrate species listed as threatened by the International Union for Conservation of Nature (IUCN; version 2016-1) with potential habitat within each 12-digit hydrologic unit code (HUC) in the conterminous United States.

Justification: Biodiversity is a primary measure of conservation importance. The underlying assumptions driving this are that 1) areas with high biodiversity will provide a source for species migration/colonization and 2) areas with high biodiversity exist because of the inherent characteristics of the surrounding landscape which support a diversity of niche space. Biodiversity indicators will be used to assess the potential importance of refugia indicators and provides the baseline "importance" value for use in identifying areas important to species conservation (e.g. using Zonation software).
Data compilation: This data set has not been processed in lieu of the availability of summed data from the EnviroAtlas (see Section Other).

2. Critical Habitat

Source: ECOS/ U.S. Fish and Wildlife Service (USFWS)
Link: USFWS Threatened & Endangered Species Active Critical Habitat Report
Reference:

- USFWS Threatened & Endangered Species Active Critical Habitat Report

Description: The critical habitat layer provides information on the proposed and final critical habitat for species listed as Threatened and Endangered by the USFWS or that are jointly managed by the USFWS and National Marine Fisheries Service (NMFS). Details include the scientific name, where a species was listed, current federal listing status, and spatial derived critical habitat areas.
Justification: Critical habitat refers to a specific area within a geographic region, occupied by the species, which is deemed essential for the conservation of an endangered or listed species. These areas may represent refugia for Species of Greatest Concern.
Data compilation: This data is available within the project geodatabase but has not been processed for inclusion in the analysis. The dataset may be redundant with those available in the EnviroAtlas unless a species-specific analysis is required.

New Mexico State Layers

1. Crucial Habitat*

Source: NM CHAT
Link: Data - NM CHAT
Reference:

- New Mexico Crucial Habitat Data Set. New Mexico Crucial Habitat Assessment Tool: mapping fish and wildlife habitat in New Mexico. New Mexico Department of Game and Fish and Natural Heritage New Mexico. Published 12/10/2013. Accessed 4/23/2024. http://nmchat.org/

Description: The New Mexico Crucial Habitat Assessment Tool (NM Chat) is collaborative project between the New Mexico Department of Game & Fish, Natural Heritage New Mexico at the University of New Mexico, and the Western Association of Fish and Wildlife Agencies. It provides spatial information on the conservation of animals, plants, and their habitat across

New Mexico. The Crucial Habitat rank (square mile) based on species of concern, wildlife corridors, terrestrial and aquatic species of economic and recreational importance, watershed status, wetland and riparian areas, large natural areas, and natural vegetation communities of concern.
Justification: NM CHAT provides detailed information on areas that are regarded as Crucial Habitat; important ecological communities and places that are expected to contain the resources or for the continued health of fish and wildlife populations. We will use NM CHAT scores to facilitates the incorporation of ecosystem features and importance rankings in an assessment of indicator importance.
Data compilation: NM CHAT shapefile has been downloaded and processed so that we can produce metrics for refugia as appropriate to analysis needs. This data will be used in one of two ways: First, as a unit of analysis where input data has a resolution that matches or is finer than that of the CHAT. This will allow future CHAT estimates to consider other variables (such as topographic diversity). Second, we will use the CHAT scores as a basis for tests of indicator importance in a similar manner to the biodiversity data where high values are correlated to the presence of landscape metrics.

2. Land Ownership

Source: U.S. Bureau of Land Management (BLM) New Mexico
Link: **BLM NM Surface Management Agency | BLM NM Surface Management Agency | BLM GBP Hub (arcgis.com)**
Reference:

- **BLM NM Surface Management Agency | BLM NM Surface Management Agency | BLM GBP Hub (arcgis.com)**

Description: Data was collected by U.S. BLM and various field offices. Data describes the surface owner or manager of land parcels, which in most cases are the same agency or person. Where this is not the case, the manager is usually indicated. BLM's Master Title Plats are the official land record of the federal government and the primary data source for federal lands.
Justification: Land ownership can represent management potential and challenges. Analysis of refugia potential may consider adjacent land ownership patterns and or be filtered by land management agency.
Data compilation: This data is available in the project geodatabase but has not yet been processed for analysis.

3. Conservation Opportunity Areas*

Source: New Mexico SWAP
Link: ERT/NM_SWAP_Conservation_Opportunity_Areas (MapServer) (unm.edu)
Reference:

- New Mexico Department of Game and Fish. 2016. State Wildlife Action Plan for New Mexico. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA

Description: Conservation Opportunity Areas (COAs) are identified in New Mexico's State Wildlife Action Plan (SWAP). These COAs are considered to have superior potential for

conserving SGCN. While COAs are not regulatory, they serve as focal points for habitat and wildlife restoration efforts, aligning with the SWAP.
Justification: The COAs provide a landscape level view of high biodiversity areas within New Mexico, specifically focused on conserving SGCN.
Data compilation: A shapefile of NM COA has been used to summarize most climate, topographic and soils variables to facilitate an analysis of current COA potential for containing macro and microrefugia.

Vegetation Layers

1. Ecological Response Units

Source: USDA Forest Service, Southwestern Region
Link: **r03/r03_Ecological_Response_Units_01 (MapServer) (usda.net)**
Reference:

- Wahlberg, M. M., F. J. Triepke, W. A. Robbie, S. H. Strenger, D. Vandendriesche, E. H. Muldavin, and J. R. Malusa. 2013. Ecological Response Units of the Southwestern United States. USDA Forest Service Forestry Report Southwestern Region, Regional Office, Albuquerque, NM. 201 pp. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd609789.pdf

Description: The Ecological Response Units (ERU) framework represents all the major ecosystem types of the southwest region and a coarse stratification of biophysical themes. The ERUs are map unit constructs, grouping of finer vegetation classes with similar site potential and disturbance histories (Wahlberg et al. 2013). ERUs can be polyphyletic, with an individual vegetation type being indicative of more than one ERU.
Justification: ERU framework facilitates landscape planning and analyses through stratification of the landscape into meaningful units. ERUs provide a structured approach to understanding ecosystems and analyzing landscapes.
Data compilation: This data is available in the project geodatabase but has not yet been processed for this analysis.

2. U.S. National Vegetation Classification

Source: United States National Vegetation Classification
Link: **The U.S. National Vegetation Classification – Your guide to the nations vegetation (usnvc.org)**
Reference:

- Federal Geographic Data Committee (FGDC). 2008. Vegetation Classification Standard, FGDC-STD-005, Version 2. Washington, DC, USA. Federal Geographic Data Committee. 2008. The National Vegetation Classification Standard, Version 2. FGDC Vegetation Subcommittee. FGDC-STD-005-2008 (Version 2). 126 pp.

Description: The United States National Vegetation Classification (USNVC) is a collaboration between the Ecological Society of America, NatureServe, and various federal agencies. The

USNVC is a hierarchical classification, from coarse to fine, of all vegetation types in the United States. Standards for both data collection and analysis ensure consistent vegetation data reporting.

Justification: The USNVC provides a common language and its hierarchical format allows for scalable classification for modeling, mapping wildlife habitat and studying patterns of vegetation change over time.

Data compilation: This data has been downloaded but not yet processed. This data may be used later to filter results or perform additional analysis to determine important metrics . Currently, we are relying on more generic measures of plant productivity including Actual Evapotranspiration, and Existing Vegetation Cover (percent cover) and Existing Vegetation Type (forest, shrub, herb) that can provide more comparable metrics across the diverse landscape types in New Mexico.

3. Existing Vegetation Cover, Height, and Type

Derived data:

a) Percent Cover of Vegetation
b) Diversity Vegetation Type

Source: LandFIRE

Link: LANDFIRE Program: Data Product Mosaic Downloads

Reference:

- Rollins, M. G. 2009. LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. *International Journal of Wildland Fire*, 18(3), pp. 235-249.

Description: LANDFIRE (LF) provides vegetation, fuel, disturbance, and fire regime data for the United States. There are over 20+ products available including existing vegetation type (EVT), existing vegetation height (EVH) and existing vegetation cover (EVC). LF vegetation maps units are derived from NatureServe's ecological classification system, a midscale national consistent format. EVT data represents the species composition currently at a given site. EVH data represents the average height of dominant vegetation for a 30m grid cell. EVC data represents the vertically projected percent cover of the live canopy layer for a 30m grid cell. EVT, EVH and EVC data were mapped through predictive modelling, using a combination of field reference data, Landsat imagery, and spatially explicit biophysical gradient data.

In addition to vegetation data, LANDFIRE offers disturbance products. The annual disturbance data 1999-Current year (DistYear) illustrates the change in the landscape caused by both management activities and natural disturbance for a given year. This data is a compilation of Landsat-derived indices (e.g., Normalized Difference Vegetation Index (NDVI) and Difference Normalized Burn Ratio (dNBR); disturbance Event parameters; fire severity and extent mapping from Monitoring Trends in Burn Severity (MTBS), Burned Area Reflectance Classification (BARC), and Rapid Assessment of Vegetation Condition after Wildfire (RAVG) fire mapping; Protected Area Database (PAD) ownership data; and Burned Area Essential Climate Variable (BAECV) data.

The LF Vegetation disturbance (VDist) is a composite of DistYear products for the previous 10 years. Disturbances are grouped by type or cause, disturbance severity and time since disturbance.
Justification: The LF vegetation data gives a seamless picture of the vegetation composition in the Southwest. The data format is commonly accepted and allows for a more complete multidimensional assessment of potential refugia sites. The LF disturbance data provides temporal and spatial information on landscape changes. This data may be used to identify areas with forest cover, Net Primary Productivity (NPP) variation, and other factors that might be related to climate buffering capacity.
Data compilation: This data is available in the project geodatabase. Though several studies point to the importance of forest cover for moderating microclimate variations, a state-wide application of criteria such as percent Forest cover may be misleading because it will introduce a bias against non-forested areas. Further discussion is needed before including a Forest Cover metric. We did generate data on percent cover (any vegetation) and diversity of vegetation type. The diversity metric was calculated by creating bins of low (<30%), medium (30-60) and high (>60%) percent cover for trees, shrubs and herbaceous types. These were then used to calculate local diversity by generating Shannon and Simpson diversity indices for 3x3 and 9x9 unit space.

Geography/Soils

1. Land Facets Data*

Derived data layers:

a) HLI
b) Topofacets
c) Landform
d) Soil Order
e) Soil ID
f) Topofacets Diversity

Reference:
Carroll C., D. R. Roberts, J. L. Michalak, et al. 2017. Scale-dependent complementarity of climatic velocity and environmental diversity for identifying priority areas for conservation under climate change. *Global Change Biology,* 23, pp. 4508–4520. https://doi.org/10.1111/gcb.13679

Source of data: Adaptwest: The Adaptwest project focuses on combining information from multiple types of conservation targets into an integrated multi-criteria plan for conservation in the face of climate change.

Description: From author abstract: “We developed a dataset categorizing the North American continent into physical habitat types at 100m resolution. The input data used included elevation and soil type, using the methodology described below. Download links are available at the bottom of this page. Both land facet and topofacet data are available using either latitudeadjusted elevation or untransformed elevation values. We also provide the components of the land facet data separately as HLI(Heat Load Index), landform, elevation and soils rasters" (Michalak, J., C. Carroll, et al. 2015).

Justification: Data on physical features such as topography, soils, and geology influence patterns of biodiversity (Carroll et al., 2017). The presence of spatial variations in topographic and soil conditions will support the persistence of local climate patterns and gradients (e.g., higher elevations will still be cooler than lower elevations, although both will likely be warmer) as climates changes. The land facet approach was considered a "coarse-filter" representation strategy where a diversity of physical habitat types or "land facets" are identified for protection (Carroll et al. 2017). Carroll argues that, though an imperfect surrogate, land facets are a surrogate for direct biodiversity data in conservation planning processes.

Data processing: We downloaded data from https://adaptwest.databasin.org/pages/adaptwest-landfacets/ (4/11/2024). We calculated Shannon's and Simpson diversity metrics for 3x3 and 9x9 unit space using the Focal Diversity Tool available with the DiversityAnalysisTools with ArcPro.

2. DEM (Digital Elevation Model)*

Derived Data Layers:

a) Slope (percent and degree)
b) Aspect (degree and radian)
c) Northness
d) Eastness
e) Southness
f) Heat Load Index (HLI)
g) Topographic Position Index (TPI)
h) Compound Topographic Index (CTI)/Topographic Wetness Index (TWI)
i) Topographic Convergence Index (TCI)
j) Landform (further derived: presence of valley)
k) Landscape diversity metrics: Vector Ruggedness Index (VRI), Ruggedness, Roughness, Slope standard deviation in 3x3 and 9x9 spatial units
l) Shannon and Simpson Diversity Metrics: Aspect, Slope, HLI, Landform, Elevation

Source1: USGS Digital Elevation Model
Source2: 1 degree digital elevation model for Colorado, New Mexico, Utah and Arizona, USA
Link: 1 degree digital elevation model for Colorado, New Mexico, Utah and Arizona, USA | Data Basin
Description: The USGS National Elevation Dataset (NED) provides seamless raster elevation data of the conterminous United States, Alaska, Hawaii, and territories. Data is developed from diverse sources and processed with a consistent resolution, coordinate system, elevation units, and horizontal and vertical datums. Vector contour lines are derived from the gridded 3D

elevation data using automated and semi-automated processes. Contour intervals are assigned by 7.5-minute quadrangle; therefore, a vector dataset is not visually seamless across quadrangle boundaries. Datasets are available in various extents and locations across New Mexico. Over 30 regions were necessary to cover New Mexico, all with the same NED 1/3 arc-second contours for New Mexico, 1 x 1 degree extent. We downloaded and used a processed version of this data from DataBasin (see link above).

Justification: Elevation plays a pivotal role in shaping the spatial structure of plant and animal communities. Altitudinal gradients encompass climatic and environmental gradients including net primary production (Nogués-Bravo et al. 2008). Additionally, evidence indicates that warming is amplified with elevation changes, causing high elevation regions to experience more rapid changes than do lower elevations (Pepin et al. 2015). Topographic conditions drive patterns in species diversity (see discussion in Literature review) and several metrics were calculated from the DEM layer to describe local conditions. These metrics form the basis of landscape diversity metrics, which are important indicators of potential refugia and are often associated with species diversity.

Data compilation: The 1 degree data set was downloaded and processed using various tools in Spatial Analysts to produce a range of topographic variables including Slope, Curve, Ruggedness, Roughness and Landform (Geomorph). Northness was calculated as the cosine of Aspect (radians); Eastness as the sine of Aspect (radians); Southness as -cos(Aspect)xsin(slope). Each of these was then summarized (mean) using Zonal Statistics tool for each HUC12 and COA. We calculated Shannon's and Simpson diversity metrics for 3x3 and 9x9 unit space using the Focal Diversity Tool available with the DiversityAnalysisTools with ArcPro. Continuous variables (elevation, aspect) were first categorized into bins to facilitate calculations.

3. Stream Temperature

Source: NorWeST

Link: [NorWeST Stream Temperature Regional Database and Model | Water and Watersheds (W&W) Program - USDA Forest Service Science - RMRS]

Reference:

- Isaak, D., S. Wenger, E. Peterson, J. Ver Hoef, D. Nagel, C. Luce, S. Hostetler, J. Dunham, B. Roper, S. Wollrab, G. Chandler, D. Horan, and S. Parkes-Payne. 2017. The NorWeST summer stream temperature model and scenarios for the western U.S.: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. *Water Resources Research*, 53, pp. 9181-9205.

Description: The NorWeST webpage hosts stream temperature data and climate scenarios for streams and rivers across the western U.S. Using a framework provided by the National Hydrology Dataset (NHD), stream temperature records were organized from more than 100 agencies in the western U.S to create the NorWeST database with >220,000,000 temperature recordings from >22,700 stream and river sites (Isaak et al. 2017). Spatial-stream-network models were fitted to a subset of those data describing mean August water temperatures to develop accurate temperature models, assess covariate effects, and make predictions at 1km intervals to create summer climate scenarios (Isaak et al. 2017).

Justification: Thermal regimes play a crucial role in aquatic ecosystems, influencing species distribution, abundance and productivity. Prediction of temperature in aquatic ecosystems is a critical indicator of magnitude of expected change over the next century.
Data compilation: This data set is available in the geodatabase but is not yet processed for current analysis.

4. Geology

Source: New Mexico Bureau of Geology and Mineral Resources
Link: **Browse rgis data New Mexico Bureau of Geology 500k Surface Geology (unm.edu)**
Reference:

- Geologic Map of New Mexico, New Mexico Bureau of Geology and Mineral Resources, 2003, Scale 1:500,000

Description: The Geological Map of New Mexico, published in 2003, is the first 1:500,000 scale geological map of New Mexico to be published since 1965. It was developed over the course of 20 years through the collective input of geologists throughout the state of New Mexico. This digital map was based upon the earlier Geologic Map of New Mexico by Orin J. Anderson and Glen E. Jones, with significant revisions. Available spatial data include geology and formations, faults, and dikes.
Justification: Geology shapes the physical environment, influencing where plants and animals can persist. Incorporating geology is vital for a more complete picture of the ecosystem processes.
Data compilation: This data set is available in the geodatabase but is not yet processed for current analysis. Data available here may be redundant with other sources (e.g., Land Facet analysis).

5. Stream Flow

Source: U.S. Forest Service Rocky Mountain Research Station and the Office of Sustainability and Climate.
Link: **USDA Forest Service FSGeodata Clearinghouse – Download National Datasets**
Reference:

USDA Forest Service FSGeodata Clearinghouse – Download National Datasets

Description: Actual flow data is only available for a small subset of stream segments; therefore, flow data for other streams and rivers must be modeled or extrapolated. Streamflow data was modeled for each stream segment in the 1:100,000-scale National Hydrography Dataset (NHDPlus version 2) across the contiguous United States, for the historical period (1977–2006) and two projected future time periods (mid-century [2030–2059], and end-of-century [2070–2099]. Models are based on gridded simulations of daily total runoff. Future projections are based on five global climate models (GCMs) associated with the Representative Concentration Pathway (RCP) 8.5 high emissions scenario.
Justification: The flow regime is fundamental in determining the ecological and physical characteristics of a river or stream. The modeled stream flow data enable the analyses of both

historic and future flow patterns and identification of relative stability under warming conditions.
Data compilation: This dataset has been downloaded but has not yet processed. It will be used for analysis if aquatic environments.

6. Snow

Derived Data Layer:

a) Snow Water Equivalent, April 1st

Source: Natural Resources Conservation Service (NRCS)
Link: **Snow Survey and Water Supply Forecasting Program | Natural Resources Conservation Service (usda.gov)**
Reference:

- Fleming, S. W., L. Zukiewicz, M. L. Strobel, H. Hofman, and A. G. Goodbody. 2023. SNOTEL, the soil climate analysis network, and water supply forecasting at the natural resources conservation service: Past, present, and future. *JAWRA Journal of the American Water Resources Association*, 59(4), pp. 585-599**.**

Description: The NRCS monitors snow and water resources across the U.S. An online platform provides current and historic hydrometeorological data related to snow and water from various sources including the U.S. Bureau of Reclamation, Soil Climate Analysis Network, automated snow telemetry (SNOTEL) stations, USGS, and the Applied Climate Information System (ACIS). In New Mexico there are 29 active automated snow telemetry sites that collect real-time data about snow, precipitation, air temperature, and soil moisture. Manual snow surveys are also conducted each winter. The combined data are used to provide streamflow forecasts for the region.
Justification: The snowpack is a critical resource, particularly in dry regions of the Southwest where it acts as a natural water reservoir by collecting snow in the winter and releasing water during the spring thaw. As such, snowpack represents a major source of flow for stream and river ecosystems. Reductions in overall snowpack and in the timing of snowpack melt have implications for both upper- and lower-elevation habitats.
Data compilation: Data is downloaded but not yet summarized. Use of this dataset is pending analysis of species distribution models and second-year activities related to aquatic ecosystem assessment. Alternative source also identified from BOR data (see Climate Data).

7. Soils*

Derived Data Layers:

a) Average water storage: avwatstr
b) 0 - 100 cm water storage: watstr100
c) Minimum average depth to bedrock in map unit: MinDth
d) Dominant texture(s): Texture
e) Soil temperature/moisture regime: soil_clima

f) Dominant soil order(s): Order

Source: Conservation Biology Institute
Link: Soils of New Mexico, Arizona, Utah and Colorado, USA | Data Basin
Reference:

Soils of New Mexico, Arizona, Utah and Colorado, USA | Data Basin

Description: This dataset was developed using the STATSGO2, a 1:250,000-scale U.S. soils database with soil descriptions from the Natural Resources Conservation Service (NRCS) website. The main soil characteristics described by this dataset are soil order, texture, climate regime, and caliche.
Justification: Soils play a vital role in plant nutrition providing essential elements including nitrogen, phosphorus, and potassium. Soil composition may also be acidic, sandy, or clay-rich, each supporting different plant species. Soils therefore act as filters influencing the geographic distribution of plants within an ecosystem. Soil properties (water holding capacity, texture and composition) have also been related to drought resilience and climate refugia.
Data compilation: Each of the derived variables were summarized by HUC12 and COA.

Assessment/Climate Layers

1. Forests to Faucets*

Derived Datasets (HUC12):

a) Relative Development Threat to Important Drinking Water Watersheds 2010-2040 (low)
b) Relative Development Threat to Important Drinking Water Watersheds 2010-2090 (low)
c) Relative Development Threat to Important Drinking Water Watersheds 2010-2040 (high)
d) Relative Development Threat to Important Drinking Water Watersheds 2010-2090 (high)
e) Relative Water Yield Threat to Important Drinking Water Watersheds 2010-2040 (low)
f) Relative Water Yield Threat to Important Drinking Water Watersheds 2010-2090 (low)
g) Relative Water Yield Threat to Important Drinking Water Watersheds 2010-2040 (high)
h) Relative Water Yield Threat to Important Drinking Water Watersheds 2010-2090 (high)
i) Forest Cover
j) Cover Natural Areas

Link: Forests to Faucets (usda.gov)
Reference:

- Mack, E., R. Lilja, S. Claggett, G. Sun, and P. Caldwell. 2022. Forests to Faucets 2.0: Connecting forests, water, and communities. General Technical Report. WO-99. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 32 pp. https://doi.org/10.2737/WO-GTR-99.

Description: The Forests to Faucets program uses geospatial modelling to assess all 83,314 HUC12 watersheds in the U.S. to identify those watersheds that are important to downstream surface drinking water supplies as well as evaluate a watershed's natural ability to produce

clean water. Forest to Faucets 2.0 (F2F2) is a USDA-led program that builds upon an earlier version from 2011 with updated methodology and data inputs. F2F2 provides information on the watersheds that are most important to surface drinking water, type of forest ownership, and where they are threatened by insects and disease, wildfire, land use change, or climate change that decreases water yield (Mack et al. 2022). Threat from climate change is an additional component of the newer version of Forest to Faucets.
Justification: F2F2 provides a landscape-scale analysis of watersheds and the extent to which they are threatened by development, insects and disease, wildland fire, and climate change.
Data compilation: Data is already available and summarized by the HUC12 analysis unit. We further analyze data for each COA.

2. Climate Stress by Subwatershed

Source: NorWeST
Link: **NorWeST Stream Temperature Regional Database and Model | Water and Watersheds (W&W) Program - USDA Forest Service Science - RMRS**
Reference:

- Isaak, D., S. Wenger, E. Peterson, J. Ver Hoef, D. Nagel, C. Luce, S. Hostetler, J. Dunham, B. Roper, S. Wollrab, G. Chandler, D. Horan, and S. Parkes-Payne. 2017. The NorWeST summer stream temperature model and scenarios for the western U.S.: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. *Water Resources Research*, 53, pp. 9181-9205.

Description: Seven climate stress variables were assessed and assigned a value of 1 if they passed the threshold and 0 otherwise. Variables and thresholds include: Absolute change in length-weighted number of winter floods > 4; Percent change in length-weighted 25-year flood > 25; Percent change in length-weighted decadal low flow > 25; Percent change in snow water equivalent > 25; Percent change in snow residence time > 25; Percent change in 90th percentile number of summer dry days > 25; Historical (1993-2011) stream temperature > 18 °C (i.e., above 20 °C with a 2 °C temperature increase). Values were summed and divided by the number of variables with data in each subwatershed to identify the percentage of variables with projected changes over the threshold. Severity levels were categorized as <25%, medium ≥ 25% - <50% and high ≥ 50%. Future data is for the time period 2070-2099, using RCP 8.5. Data sources included the Streamflow Metrics data, National Forest Climate Change maps, and the NorWeST Stream Temperature dataset.
Justification: The data provides insight into identifying climate stress patterns at the subwatershed level.
Data compilation: This dataset has not yet been processed for analysis.

3. Climate Dissimilarity*

Source: AdaptWest Analysis
Link: **Climatic dissimilarity for North America | AdaptWest (databasin.org)**
References:

- Carroll, C. 2018. Climatic dissimilarity data for North America at 1 km resolution. https://doi.org/10.5281/zenodo.1473825. Available online at https://adaptwest.databasin.org/pages/climatic-dissimilarity.
- Belote, R. T., C. Carroll, S. Martinuzzi, J. Michalak, J. W. Williams, M. A. Williamson, and G. H. Aplet. 2018. Assessing agreement among alternative climate change projections to inform conservation recommendations in the contiguous United States. *Scientific Reports*, 8(1), 13 pp.
- Mahony C. R., A. J. Cannon, T. Wang, S. N. Aitken. 2017. A closer look at novel climates: new methods and insights at continental to landscape scales. *Global Change Biology*, 23, pp. 3934-3955.

Description: Climate dissimilarity is a metric of climate-change exposure that summarizes the overall change in climate based on an assortment of climate variables. The metric indicates how different a future climate at a location will be when compared to the current conditions. The metric uses multivariate climate variables, derived from 11 biologically relevant temperature and precipitation variables, instead of mean temperature shifts. Variables are analyzed using principal components analysis (PCA) for baseline conditions and projected future climate conditions (RCP 4.5: moderate emission scenario, RCP 8.5: high emission scenario). Results provide a multivariate representation of climate change.

Justification: Climate dissimilarity data provides insight into how climate change will impact different regions and aid in identifying both suitable and unsuitable potential refugia.

Data compilation: Data was downloaded, clipped to New Mexico boundary and reprojected into NAD83 for analysis. Values were then summarized by HUC12, COA, and Ecoregion.

4. Climate Velocity*

Derived Data:

A. Backward multivariate climatic velocity in km_yr for ensemble RCP4.5 projection 1995-2055
B. Backward multivariate climatic velocity in km_yr for ensemble RCP4.5 projection 1995-2055
C. Forward multivariate climatic velocity in km_yr for ensemble RCP8.5 projection 1995-2085
D. Forward multivariate climatic velocity in km_yr for ensemble RCP8.5 projection 1995-2085

Source: AdaptWest

Link: Velocity of climate change grids for North America | AdaptWest (databasin.org)

References:

Citations for the CMIP6-based velocity data are:

- Carroll, C. 2023. Velocity of climate change for North America based on CMIP6 GCMs [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10631707
- Carroll C. and C. R. Mahony. 2024. Sources of uncertainty in estimation of climate velocity and their implications for ecological and conservation applications. Preprint available at https://osf.io/q6ryk

Methodology citations:

- Hamann, A., D. R. Roberts, Q. E. Barber, C. Carroll, and S. E. Nielsen. 2015. Velocity of climate change algorithms for guiding conservation and management. *Global Change Biology,* 21, pp. 997-1004, DOI: 10.1111/gcb.12736.
- Carroll, C., J. J. Lawler, D. R. Roberts, and A. Hamann. 2015. Biotic and climatic velocity identify contrasting areas of vulnerability to climate change. *PLOS ONE*, 10(10), e0140486.

Data citation:

- CMIP5 : AdaptWest Project. 2015. Gridded climatic velocity data for North America at 1km resolution
- CMIP6: AdaptWest Project. 2023. Gridded CMIP6-based climatic velocity data for North America at 1km resolution. Available at adaptwest.databasin.org.

Description: Climate velocity represents the speed at which an individual species must move location to keep within the same climate regime in the future. It is calculated by dividing the rate of climate change by the rate of spatial climate variability. The AdaptWest algorithm conforms to standard calculations of climate velocity if climate equivalents are nearby; otherwise, the algorithm extends the search refugia globally. This provides both forward and backwards calculations, allowing better understanding of species' migration rates and minimum migration rates based on projected climate scenarios. The datasets are based on Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate data from the historical normal period and climate change projections from CMIP5/CMIP6 (Coupled Model Intercomparison Project) models.
Justification: The data is important in assessing how quickly species need to adapt or migrate to keep pace with climate change. It can also assist in locating future refugia from climate change.
Data compilation: Data was downloaded, clipped to New Mexico boundary, and reprojected into NAD83 for analysis. Values were then summarized by HUC12, COA, and Ecoregion.

5. Climate Corridors*

Derived Data Layers:

a) HUC12_CorridorCount: Attribute Count of Lines represents relative number of corridor reaches in HUC12
b) COA_CorridorCount: Attribute Count of Lines represents relative number of corridor reaches in COA

Source: databasin.org
Link: climate_connectivity_cores_corridors | Data Basin
Reference:

- McGuire, J. L., J. J. Lawler, B. H. McRae, T. A. Nuñez, and D. M. Theobald. 2016. Achieving climate connectivity in a fragmented landscape. *Proceedings of the National Academy of Sciences*, 113(26), pp. 7195-7200.

Description: Climate gradient corridors were created for the U.S. using the Climate Linkage Mapper Toolbox. This uses the climate-gradient corridor method introduced by Nuñez et al. 2013, whereby corridors are identified that fall along climatic gradients while minimizing resistance to movement through human modification.
Justification: Habitat fragmentation limits a species' ability to track suitable climates as they rapidly change (McGuire et al. 2016). Identification of climate corridors provides insight into the capacity for species to adapt under climate change and areas where access to suitable corridors may be a limitation.
Data compilation: Downloaded data, projected to NAD83, clipped to New Mexico, and then used Spatial Analysts tool> Summarize Within, to count number of active lines per unit of interest for each HUC12, COA, and Ecoregion.

6. Climate data*

Derived Data:

a) Historic Precipitation and Temperature Variables (1970-2010) [BioClimate Variables: Bio1, Bio2, Bio3, Bio4, Bio5, Bio6, Bio7, Bio8, Bio12, Bio13, Bio14, Bio15, Bio16, Bio17, Bio18, Bio19]
b) Future Precipitation and Temperature Variables (2040-2060 = "2050"; 2060-2090 = "2080") under RCP 4.5 [BioClimate Variables Bio1, Bio2, Bio3, Bio4, Bio5, Bio6, Bio7, Bio8, Bio12, Bio13, Bio14, Bio15, Bio16, Bio17, Bio18, Bio19]
c) Magnitude change in Historic and Current conditions for BioClimate Variables
d) Actual and Potential Evapotranspiration (AET, PET; BOR datasets)
e) April Snow Water Equivalent (SWE; BOR datasets)
f) Climatic Moisture Index (CMI)
g) Heat Moisture Index (HMI)
h) Aridity Index (AI)

Source:

1. WorldClim CMIP5 (30 arc second BioClimate indicators); CMIP6

https://www.worldclim.org/data/v1.4/formats.html#Data%20Format
PCMDI - CMIP5 Overview (llnl.gov) CMIP6 Homepage (llnl.gov)

2. "BOR Data": Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections. http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf;

References:

- Fick, S. E. and R. J. Hijmans. 2017. WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, 37(12), pp. 4302-4315.
- Eyring, V., S. Bony, G. A. Meehl, C. A. Senior, B. Stevens, R. J. Stouffer, and K. E. Taylor. 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6)

experimental design and organization. *Geoscientific Model Development*, 9(5), pp. 1937-1958.

- Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy (2007), 'Fine-resolution climate projections enhance regional climate change impact studies', *Eos Trans*. AGU, 88(47), 504
- Reclamation, 2013. 'Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with preceding Information, and Summary of User Needs', prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado. 47pp.

Description: Data from the WorldClim website were downloaded for historic and future time periods (2040 under RCP 4.5, CMIP5) and for each of the models available. WorldClim provides high resolution global weather and spatial data. Data is available for historical and future conditions. From the WorldClim site: “Bioclimatic variables are derived from the monthly temperature and rainfall values in order to generate more biologically meaningful variables. These are often used in species distribution modeling and related ecological modeling techniques. The bioclimatic variables represent annual trends (e.g., mean annual temperature, annual precipitation) seasonality (e.g., annual range in temperature and precipitation) and extreme or limiting environmental factors (e.g., temperature of the coldest and warmest month, and precipitation of the wet and dry quarters).” Data for all available CMIP5 models were downloaded from the BOR website for: Snow Water Equivalent, Actual and Potential Evapotranspiration. Monthly downscale data was downloaded for periods 1950-2099.
Justification: These data provide the basis for estimating change in climate across landscapes. Bioclimate indicators are used to model species habitat under current and future conditions. Hydrological variables obtained from the BOR allow us to calculate several
Data compilation: Each data set was reprojected into NAD 83 and clipped to New Mexico. A mean ensemble was generated for each Bioclimate variable, and this was used to estimate change from historic (ensemble – historic or magnitude change for temperature variables and ensemble-historic/historic or percent of normal for precipitation variables). Seasonal estimates of EAT and PET were calculated by quarter calendar year. Heat Moisture Index (HMI) is estimated as Mean Annual Temperature +10/Mean Annual Precipitation/1000. Climate water Deficit (CWD) was calculated by subtracting AET from PET. We calculated Shannon’s and Simpson diversity metrics for 3x3 and 9x9 unit space using the Focal Diversity Tool available with the DiversityAnalysisTools with ArcPro.

7. Watershed Climate Vulnerability

Source: United States Forest Service (USFS)
Link: R03_CCVA_Watersheds - Overview (arcgis.com)
Reference: Triepke, J. Dataset: R03_CCVA_Watershed, vector digital data, R03_CCVA_Watershed (arcgis.com), USDA Forest Service, Southwestern Region Rocky Mountain Research Station
Description: Climate Change Vulnerability Assessments (CCVAs) examine the possible effects of climate change on national forests and associated resources. This assessment provides details

of why a resource is vulnerable and possible available actions. As partial fulfilment of the CCVA, a spatial dataset was created for major upland ecosystems of Arizona and New Mexico. Vulnerability was based on the projected climate departure from the historic climate for a given Ecological Response Unit (ERU) and location. Vulnerability ratings are low, moderate high, or very high.

Justification: This data may provide a useful measure of conservation value if collaborators agree that areas of low vulnerability should be targets for conservation action.

Data Compilation: Not yet processed for inclusion in analysis.

8. Drought Indictors*

Derived Data:

A. Aridity Index
B. Available soil moisture (soils)
C. Climatic Water Deficit
D. Dry degree days

Link: Historical and future ecological drought conditions for rangelands of the western U.S. | U.S. Geological Survey (usgs.gov) https://doi.org/10.5066/10.5066/P97S8RAC

Reference: Schlaepfer, D. R., C. M. Andrews, and J. B. Bradford. 2022. Historical and future ecological drought conditions for rangelands of the western U.S.: U.S. Geological Survey data release, https://doi.org/10.5066/P97S8RAC.

Description: This data describes geographic and temporal patterns in climate and drought exposure of western rangelands under historic (1971-2010) and future (2021-2060 and 2061-2100) climate scenarios. A water balance model was used to estimate several metrics that represent water availability and drought at a 10-km resolution. Original abstract: “These NetCDF data were compiled to investigate how rangelands in the western U.S. are limited by access to water. As a result, these ecosystems may be especially vulnerable to changes in water availability and drought as a result of climate change. This project utilized an ecosystem water balance model to quantify spatial and temporal patterns of rangeland ecological drought conditions under historical and future climate conditions. Water balance results were used to estimate several metrics that describe the seasonal timing and amount of moisture available for plant utilization in western rangelands. These data represent different aspects of water availability and drought. They are based on 1/16-degree gridded simulations using the SOILWAT2 ecosystem water balance model (Schlaepfer et al. 2021) for areas of the western USA where the models represent vegetation structure and ecohydrological upland processes under historical and future condition, i.e., drylands where aridity index (AI) = ratio of annual precipitation amount to annual potential evapotranspiration, is less than 0.65 excluding the warm-moist portion (areas where mean monthly temperature > 4 C and April-June precipitation > 75 mm). The temporal coverage of these NetCDF data consist of a historical annual or quarterly times-series over 1971-2010 (simulations driven by daily meteorological inputs from Livneh et al. 2013) and future projected climatologies (means across years) over 2021-2060 and 2061-2100 using downscaled output from 11 climate models that participated in CMIP5

experiment RCP4.5 (representative concentration pathway). The 11 climate models include: CanESM2, CESM1-CAM5, CSIRO-Mk3-6-0, CNRM-CM5, FGOALS-g2, FGOALS-s2, GISS-E2-R, HadGEM2-ES, inmcm4, IPSL-CM5A-MR, MIROC-ESM (downscaled for North America and obtained from the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projects" archive; Maurer et al. 2007). Soil properties were derived from the ISRIC WISE30sec dataset (Batjes 2016). To capture the spread across SOILWAT2 simulation runs based on the 11 GCMs for each future time period and RCP, we provide data representing the gridcell-wise median, low (2nd lowest ranked value), high (2nd largest ranked value), and robustness (number of runs that agree in the direction of change between the future projected median and historical conditions). These data were created by the U.S. Geological Survey."
Justification: "The purpose of these data are to describe geographic and temporal patterns in climate and drought exposure of dryland ecosystems in the western USA. These data were created to quantify spatial and temporal patterns of rangeland ecological drought conditions under historical and future climate conditions. These data can be used by researchers to evaluate the potential impact of changing climate conditions on soil drought within the scope defined by the study."
Data compilation: Based on 11 climate models under RCP 4.5. Downloading several variables into a folder named Soils.Schlaepfer. These were then processed for analysis in New Mexico and summarized by HUC12 and COA units.

9. Potential Riparian Vegetation

Source: USDA
Link: r03/r03_RiparianPotentialVegetation_01 (MapServer) (usda.gov)
Reference:
Description: The riparian potential vegetation data is derived from the Ecological Response Units (ERUs) layer (Version 5.2). Forest Terrestrial Ecological Unit Inventory (TEUI) survey data was cross references with ERU lists and corrections made utilizing a climate gradient to identify anomalous attribution. After a collaborative review additional date sources from Integrated Landscape Assessment Project (ILAP) data, Regional Riparian Mapping Project (RMAP) data, and subclass information from an ILAP grid analysis were incorporated. Data layers were arranged hierarchically, and smaller polygons removed.
Justification: This data might provide valuable information on riparian corridor condition that relates to the provision of species' habitat.
Data compilation: This data is available in the geodatabase but has not yet been processed for analysis. Processing is pending the discussion and selection of indicators of biological importance or conservation value.

Disturbance Layers

1. Change in Area Burned

Source: Databasin.org

Link: Simulated percent change in area burned between historical and future time periods under three climate change projections for AZ and NM, USA | Data Basin

Reference: M. A. Hemstrom, J. E. Halofsky, D. R. Conklin, J. M. Halofsky, B. K. Kerns, and D. Bachelet. In press. Assessing potential climate change effects on vegetation using a coupled model approach. *Ecological Applications*.

Description: The dataset was funded by a grant from the USFS. The dynamic global vegetation model (DGVM) MC1 was used to simulate vegetation dynamics, associated carbon and nitrogen cycle, water budget, and wildfire impacts for OR, WA, AZ, and NM. Historical data (1971-2000) provided by the PRISM group (Chris Daly, Oregon State University) at a 30 arc-second (~800 m) spatial grain. Future climate change projections (2071-2100) were run from three general circulation models: CSIRO Mk3, MIROC 3.2 medres, and Hadley CM3. The resulting data provides details on the percent change in the mean area burned per year (per ~4 km pixel) for each HUC5 watershed between historical) and future time periods.

Justification: DGVM focus on mechanisms, consequently their forecasts of future outcomes are more reliable than simple correlations (Halofsky et al. 2013). This allows for a more dependable analysis of changing vegetation patterns in response to fire under future climate scenarios.

Data compilation: Data is available in ArcGIS Online (AGOL). Analysis and inclusion are pending discussion of role of disturbances in current analyses.

2. Pyromes

Source: USFS

Link: Pyromes 20150605 - Overview (arcgis.com)

Reference: Pyromes 20150605 - Overview (arcgis.com)

Description: Pyromes refer to distinct fire activity regions that are calculated by characteristics of fire regimes, including size, frequency, intensity, season, and extent and combining these with existing datasets to represent each region. Global fire regime patterns were assessed to determine how they are related to patterns of climate, vegetation (biomes), and human activity. Bayesian clustering analysis identified five global syndromes of fire regimes (pyromes). Four pyromes represent the distinction between crown, litter, and grass fires with a non-deterministic relationship between these biomes and climate (Archibald et al. 2013). The fifth pyrome represents human-engineered modification to fire characteristics (Archibald et al. 2013).

Justification: Pyrome boundaries allow analysis of the spatiotemporal patterns of contemporary fires over different regions. They provide a framework to understand fire regions and transform with climate.

Data compilation: Data is available in AGOL. Analysis and including is pending discussion of role of disturbances in current analysis.

3. Wildfire Risk

Source: USFS

Link: Probabilistic Wildfire Risk - Overview (arcgis.com)

Reference: Probabilistic Wildfire Risk - Overview (arcgis.com)

Description: The geospatial Fire Simulation (FSim) software was developed by the USFS Missoula Fire Sciences Laboratory to estimate components of wildfire risk. FSim uses geospatial data on historical fire occurrence, weather, terrain, and fuel conditions to simulate the growth and occurrence of wildfires under thousands of hypothetical conditions to estimate the probability of a given area burning. Using the FSim software, national burn probability (BP) and conditional fire intensity level (FIL) for the conterminous U.S. were produced.
Justification: Though a natural component of Western US ecosystems, wildfire presents a huge issue for species conservation where it leads to habitat destruction and type conversion. Within New Mexico, wildfire is considered a major management consideration for most forested ecosystems.The FSim outputs can be translated into estimates of fire impacts for vegetation (e.g. risk of crown fire) that can then be incorporated into an analysis of risk.
Data compilation: Data is available in AGOL. Analysis and including is pending discussion of role of disturbances in current analysis.

Other Data Sources

1. **EnvironAtlas**

Derived data layers:

a) Average annual precipitation (inches/yr)[1]
b) Maximum amphibian species richness[2]
c) Maximum bird species richness[2]
d) Maximum mammal species richness[2]
e) Maximum summer bird species richness[2]
f) Maximum total vertebrate species richness[2]
g) Maximum winter bird species richness[2]
h) Mean amphibian species richness[2]
i) Mean bird species richness[2]
j) Mean mammal species richness[2]
k) Mean summer bird species richness[2]
l) Mean total vertebrate species richness[2]
m) Mean winter bird species richness[2]
n) Native aquatic species richness[3]
o) NIB amphibian species richness[2]
p) NIB bird species richness[2]
q) NIB mammal species richness[2]
r) NIB summer bird species richness[2]
s) NIB total vertebrate species richness[2]
t) NIB winter bird species richness[2]
u) Non-native aquatic species richness – animals[3]
v) Non-native aquatic species richness – plants[3]
w) Non-native aquatic species richness - plants and animals[3]

EnviroAtlas also has a number of land cover classification schemes that may be used to qualify conservation value including land cover, protected areas, etc.

Source: EPA EnviroAtlas
Description: EnviroAtlas was developed collaboratively by EPA in partnership with the U.S. Geological Survey (USGS), the U.S. Department of Agriculture (USDA), and other federal and non-profit organizations, universities, and communities including state, county, and city-level stakeholders. EnviroAtlas provides data at a national and community extent. The National component is summarized for the 48 mainland U.S. states by HUC 12. The community data layers are summarized by consensus block groups. There are over 400 national and community data layers. EnviroAtlas utilizes habitat models to map the number of terrestrial vertebrate species listed as threatened by the International Union for Conservation of Nature (IUCN, version 2016-1) with potential habitat within each 12-digit hydrologic unit (HUC) in the conterminous United States.
[1,2,3]Three EnviroAtlas maps (Mean, Maximum, and Normalized Index of Biodiversity [NIB]), illustrate species richness for each 12-digit HUC in the conterminous United States. Used together or independently, these maps can help identify areas of potentially low or high amphibian species richness to inform decisions about resource restoration, use, and conservation. Mean richness is a commonly used and understood value for comparison. NIB provides an index to compare a metric with other metrics across multiple project scales simultaneously. Maximum richness identifies habitats that are species rich but may not occupy large areas (e.g., linear riparian areas). w. Information on the models and data used in the USGS Core Science Analytics, Synthesis & Library’s GAP project is available on their website.
Justification: EnviroAtlas IUCN data can help identify areas of low or high threatened species richness in order to target research locations. Species richness can be used as a surrogate for measuring biodiversity to gauge the relative conservation value of a particular area (www.epa.gov/enviroatlas).
Data compilation: Data is available in AGOL. Specific layers of interest will be uploaded and used in analysis where applicable.

Sources

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IDENTIFYING AND MAPPING CLIMATICALLY STABLE MACRO- AND MICRO-REFUGIA IN NEW MEXICO: Supplemental 2. Refugia Metrics

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Supplemental 2. Final Selection of potential Refugia metrics for use in an analysis for New Mexico. Most measures in this table have been produced for analysis though development of some, indicated with and "a", are pending given further discussion. See Table 3 of main text for information on data source used for this analysis. For each metric, this table provides a definition, a data source, calculations used to generate the 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.

Category (Metric)	Definition	Direction of Effect	Data sources* (or studies citing its use)	How Calculated/Measured
Biodiversity				
Species Richness	Used to identify conservation priorities in Zonation.	Greater diversity = Better	EnviroAtlas https://www.epa.gov/enviroatlas	Various breakdowns available: all terrestrial; all amphibians; birds; mammals; reptiles; species and taxa in decline; rare, threatened, and endangered species.
Ecosystem/ Ecotypic Diversity[a]	Measure of ecological diversity.	Greater diversity = Better	Various ways to calculate this metric. Carroll et al. 2017 and Sayre et al. 2014 are examples of two methods.	Carroll et al., 2017 use a Gini-Simpson diversity index (Jost 2006)that is calculated from 11 bioclimatic variables. Variables are combined into 4 Principal Component Analysis (PCA) and Euclidean distance based on those PCA outputs are used to approximate a multivariate Mahalanobis distance for full set of variables. Sayre et al. 2014 derives Ecosystem diversity from growing degree days, an aridity index, landform, lithology, and land-cover type.
Climate Indices				
Forward Velocity	Distance a species would have to travel to find a similar climate in the future.	Lower = Better	AdaptWest, https://adaptwest.databasin.org/; Carroll & Noss 2020	Velocity metrics consider all cells and finds "matches". Measurement generated by calculating distance between given pixel and nearest pixel that is expected to have similar climate conditions under future climate.

Backward Velocity	Distance between an area’s future climate condition and an analogous climate under current conditions. The perspective is from future. Lower values (less distance) indicates that a given area is mimicking conditions of nearby areas and acting as a climate refugia..	Lower = Better	AdaptWest, https://adaptwest.databasin.org/; Carroll et al. 2017; Carroll and Noss 2020	Velocity metrics consider all cells and finds "matches". Measurement generated taking the future climate condition of pixel and then calculating distance between this and nearest existing pixel that currently has that condition.
Presence of Climate Corridors	Indicates areas that provide the best route between relatively similar climate conditions (“cores”) under current or future climate conditions. The presence of climate corridors indicates a potential path of travel for species trying to match climate conditions over time.	Presence = Better	AdaptWest, https://adaptwest.databasin.org/; Carroll and Noss 2020	Metric was created using multivariate climate variables, derived from 11 biologically-relevant temperature and precipitation variables, but not mean temperature shifts. Principal components analysis (PCA) was used to provide a multivariate representation of climate change. Areas, “cores” were identified of relatively stable climate conditions over time and corridors were identified as areas with minimal barriers to movement between cores. Degree of climate change was considered in the calculation of travel costs, in addition to physical impediments.
Climate Dissimilarity (over time)	Represents the degree to which future climate will differ from current conditions.	Context-specific	AdaptWest, https://adaptwest.databasin.org/; Carroll 2018	Metric was created using multivariate climate variables, derived from 11 biologically relevant temperature and precipitation variables, but not mean temperature shifts. Principal components analysis (PCA) was used to provide a multivariate representation of climate change
Current Climate Diversity[a]	Range of climate conditions within a study window. Often based on multidimensional analyses.	More diverse = Better	Carroll et al. 2017	Areas can be ranked based on their current degree of climate diversity. Several considerations need to be taken into account: time window, potential redundancy with other climate data measures, how well it corresponds to habitat use.

Climate Stability	Degree to which current climate changes or the difference between current and future climates.	Higher (less change) = Better	Coupled Model Intercomparison Project Phase 5 (CMIP5) data; Ashcroft et al. 2012	Calculated as absolute temperature change between current and future temperature or percent of normal (1970-2010)precipitation under future conditions.
Climatic Isolation[a]	Measures the degree to which an area is different from the climate in the surrounding area. Distinct differences might point to refugia or are indicate climatic isolation with increased potential for competitors, predators, or disease to infiltrate an area.	Context-specific	Ashcroft et al. 2012; Hampe & Jump 2011; Mosblech et al. 2011	No datasets currently available. Often based on multidimensional analyses that varies among other researchers. Need to define specifics of this analysis.
Climatic Moisture Index (CMI)	Measure of water balance.	Context-specific	CMIP5 data; Stalberg et al. 2018	CMI = (mm precipitation – mm potential evapotranspiration) using modified Penman–Monteith method
Heat Moisture Index (HMI)	Measure of temperature and water balance.	Context-specific	CMIP5 data; Haire et al. 2022	HMI = (Mean Annual Temperature +10)/(Mean Annual Precipitation/1000)
Climate Variables				
Mean Annual Temperature (MAT)**	Temperature may warm more quickly in hotter or cooler areas. Increasing temperature es in hotter areas are likely to exceed species' thermal tolerances; increasing temperatures in cooler areas are likely to increase colonization by more thermophilic species. Current and Future MAT is used to calculate the magnitude of change (climate dissimilarity), climate stability, HMI, and current climate diversity.	Context-specific	WorldCLIM CMIP5 BioClimatic Variables: https://worldclim.org/data/v1.4/cmip5_30s.html	= mean temperature over a 12 month period. Current or observed values are averaged over the period 1970-2010. Future scenarios were downloaded for the period 2040-2060. WorldClim Bioclimatic variables are derived from monthly temperature and rainfall values to represent annual trends, seasonality and extreme or limiting environmental conditions. All data were downloaded at 30-second (~1km) spatial resolution. Temperatures are calculated in C. Current or observed values are averaged over the period 1970-2010. Future scenarios were downloaded for the period 2040-2060.

Annual Minimum Temperature (AMT)	Temperatures may warm more quickly in hotter or cooler areas. Increased temperatures in hotter areas are likely to exceed species' thermal tolerances; increased temperatures in cooler areas are likely to increase colonization by more thermophilic species	Context-specific	WorldCLIM CMIP5 BioClimatic Variables: https://worldclim.org/data/v1.4/cmip5_30s.html	= Lowest monthly temperature recorded over the course of a 12 month period. WorldClim Bioclimatic variables are derived from monthly temperature and rainfall values to represent annual trends, seasonality and extreme or limiting environmental conditions. All data were downloaded at 30-second (~1km) spatial resolution. Temperatures are calculated in C. Current or observed values are averaged over the period 1970-2010. Future scenarios were downloaded for the period 2040-2060.
Annual Maximum Temperatures	Annual Maximum Temperature is used to calculate the magnitude of change, climate stability, HMI, and current climate diversity. Also represents areas of potential extreme conditions.	Higher temperatures = Worse	WorldCLIM CMIP5 BioClimatic Variables: https://worldclim.org/data/v1.4/cmip5_30s.html	=Hottest monthly temperature within a 12 month period. Current or observed values are averaged over the period 1970-2010. WorldClim Bioclimatic variables are derived from monthly temperature and rainfall values to represent annual trends, seasonality and extreme or limiting environmental conditions. All data were downloaded at 30-second (~1km) spatial resolution. Temperatures are calculated in C. Precipitation is calculated in mm. Quarters are a period of three months.
Interannual Range of Temperatures	Maximal annual range of temperature	Greater variability = Worse	WorldCLIM CMIP5 BioClimatic Variables: https://worldclim.org/data/v1.4/cmip5_30s.html	= Coldest month’s mean temperature-hottest month’s mean temperature. WorldClim Bioclimatic variables are derived from monthly temperature and rainfall values to represent annual trends, seasonality and extreme or limiting environmental conditions. All data were downloaded at 30-second (~1km) spatial resolution. Temperatures are calculated in C. Current or observed values are averaged over the period 1970-2010. Future scenarios were downloaded for the period 2040-2060.

Interannual Range of Precipitation	Seasonality of moisture	Greater variability = Worse	WorldCLIM CMIP5 BioClimatic Variables: https://worldclim.org/data/v1.4/cmip5_30s.html	= Wettest month total precipitation-driest month total precipitation. WorldClim Bioclimatic variables are derived from monthly temperature and rainfall values to represent annual trends, seasonality and extreme or limiting environmental conditions. All data were downloaded at 30-second (~1km) spatial resolution. Precipitation is calculated in mm. Current or observed values are averaged over the period 1970-2010. Future scenarios were downloaded for the period 2040-2060.
Mean Annual Isothermality	Variability in temperature over the course of a year.	Greater variability = Worse	WorldCLIM CMIP5 BioClimatic Variables: https://worldclim.org/data/v1.4/cmip5_30s.html	= Mean annual max l temperature- Mean annual minimum temperature. WorldClim Bioclimatic variables are derived from monthly temperature and rainfall values to represent annual trends, seasonality and extreme or limiting environmental conditions. All data were downloaded at 30-second (~1km) spatial resolution. Temperatures are calculated in C. Current or observed values are averaged over the period 1970-2010. Future scenarios were downloaded for the period 2040-2060.
Snow Water Equivalent (SWE) April	SWE (i.e., amount of water captured within existing snowpack) on April 1st of each year. Used to infer changes in snowpack and snowpack duration and associated water availability.	Lower = Worse	BOR CMIP5 Projections: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf	SWE is measured in mm (state, 1st day of month). Current or observed values are averaged over the period 1970-2020. Future scenarios were downloaded for the period 2040-2060.

Total Annual Precipitation (TAP)	Annual water input.	Higher = Better	Stalberg et al. 2018	= Total precipitation over a 12 month period. WorldClim Bioclimatic variables are derived from monthly temperature and rainfall values to represent annual trends, seasonality and extreme or limiting environmental conditions. All data were downloaded at 30-second (~1km) spatial resolution. Precipitation is calculated in mm.Current or observed values are averaged over the period 1970-2010. Future scenarios were downloaded for the period 2040-2060.
Total Precipitation of the Warmest Quarter	Seasonality of moisture.	Higher = Better	Stalberg et al. 2018	=Total precipitation for the warmest quarter (in New Mexico, June, July, August). WorldClim Bioclimatic variables are derived from monthly temperature and rainfall values to represent annual trends, seasonality and extreme or limiting environmental conditions. All data were downloaded at 30-second (~1km) spatial resolution. Temperatures are calculated in C. Precipitation is calculated in mm. Quarters are a period of three months. Current or observed values are averaged over the period 1970-2010. Future scenarios were downloaded for the period 2040-2060.
Potential Evapotranspiration (PET) at annual and seasonal (spring, summer) time periods	The amount of evapotranspiration that would occur if water availability were unlimited. Annual metrics represent relative water availability and is used in derived indices. Seasonal metrics have been identified as important climate change indicators.	Context-specific	BOR CMIP5Projections: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf	PET is measured in mm. Current or observed values are averaged over the period 1970-2020. Future scenarios were downloaded for the period 2040-2060.

Actual Evapotranspiration (AET) at annual and seasonal (spring, summer) time periods	AET is the measured amount of water loss from soil and plants, considering vegetation type. Seasonal metrics have been identified as important climate change indicators.	Context-Specific	BOR CMIP5 Projections: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf	AET is moisture-limited and summed over all vegetation classes and also over all snow bands; measured in mm. Annual time periods are calculated over a 12 month period, spring and summer are three month periods represented by March, April, May and June, July, August, respectively. Current or observed values are averaged over the period 1970-2020. Future scenarios were downloaded for the period 2040-2060.
Summer Vapor Pressure Deficit (VPD)	Seasonal water balance measure.	Context-specific	Derived from BOR CMIP5 data; Ashcroft et al. 2013	An alternative metric to describe variation in moisture. Calculated at the difference (deficit) between amount of moisture in the air and the amount of moisture that the air could hold. Current or observed values are averaged over the period 1970-2020. Future scenarios were downloaded for the period 2040-2060.
Mean Dry Degree Days (DDD)	This variable represents hot, dry days when dry soils are present.	More = Worse	Schlaepfer, Andrews, and Bradford 2022	Annual cumulative degree days with daily mean air temperature above 5°C, no snow cover, and soil water potential <–3.0 MPa from 0 to 100 cm depth (measured in degree days; DDD_mn Current or observed values are averaged over the period 1970-2020. Future scenarios were downloaded for the period 2040-2060.
Future Change				
Magnitude Change MAT	Component of Climate Dissimilarity (over time).	Higher = Worse	CMIP5 data; Rojas et al. 2013 and many others	=Future temperature – Current temperature
Magnitude Change Summer Maximum Temperature	Component of Climate Dissimilarity (over time).	Higher = Worse	CMIP5 data; Rojas et al. 2013 and many others	=Future temperature – Current temperature
Magnitude Change in Winter Minimum Temperature	Component of Climate Dissimilarity (over time).	Lower = Worse	CMIP5 data; Rojas et al. 2013 and many others	=Future temperature – Current temperature

Percent of Normal/ Percent changeFuture Annual Precipitation	Component of Climate Dissimilarity (over time).	Lower = Worse	CMIP5 data; Rojas et al. 2013 and many others	=(Current precipitation – Future precipitation)/Current precipitation *100 (*percent of normal*) OR (Current precipitation – Future precipitation)/Current precipitation *100 (*percent change*)
Percent of Normal/ Percent change Future Winter Precipitation	Component of Climate Dissimilarity (over time).	Lower = Worse	CMIP5 data; Rojas et al. 2013 and many others	=(Current precipitation – Future precipitation)/Current precipitation *100 (*percent of normal*) OR (Current precipitation – Future precipitation)/Current precipitation *100 (*percent change*)
Percent of Normal / Percent change Future Spring Precipitation	Component of Climate Dissimilarity (over time).	Lower = Worse	CMIP5 data; Rojas et al. 2013 and many others	=(Current precipitation – Future precipitation)/Current precipitation *100 (*percent of normal*) OR (Current precipitation – Future precipitation)/Current precipitation *100 (*percent change*)
Percent of Normal/ Percent change Future Summer Precipitation	Component of Climate Dissimilarity (over time).	Lower = Worse	CMIP5 data; Rojas et al. 2013 and many others	=(Current precipitation – Future precipitation)/Current precipitation *100 (*percent of normal*) OR (Current precipitation – Future precipitation)/Current precipitation *100 (*percent change*)
Derived Climate Variables (based on current and projected temperature and precipitation variables)				

Aridity index (AI)	The AI is a ratio of annual precipitation amount to annual potential evapotranspiration that represents the difference between rainfall and vegetative water demand. The higher the AI, the greater the water scarcity.	Higher = Worse	Global Aridity Index and Potential Evapo-Transpiration Climate Database (Fick & Hijmans 2017; Trabucco and Zomer 2018). Schlaepfer, Andrews, and Bradford 2022	AI= Mean annual precipitation/mean annual PET. Can be calculated at a variety of temporal (annual, seasonal) or spatial scales. Schlaepfer et al., 2022 provide index at 10km scale. This variable is available at annual and quarterly intervals for historic (1970-2010) and future (2021-2060) time periods. Future estimates are based on 11 climate models in from the Coupled Model Intercomparison Phase 5 (CMIP5) experiment. We downloaded data for the Representative concentration path (RCP) 4.5.
Climatic Water Deficit (CWD)	CWD is used to predict spatial patterns in vegetation (Ackerly et al. 2015), long-term climate change (McIntyre et al. 2015), and impacts of drought (Das et al. 2013; Anderegg et al. 2015; Flint et al. 2018), and has been used to assess the potential vulnerability of vegetation to future climate change (Franklin et al. 2013; McCullough et al. 2016; Thorne et al. 2017).	Lower = Better	Ackerley et al. 2020; Schlaepfer, Andrews, and Bradford 2022 (30km)	Calculated by subtracting AET from PET, capturing seasonally integrated, excess energy loading relative to water availability. Schlaepfer et al., 2022 provide index at 10km scale. This variable is available at annual and quarterly intervals for historic (1970-2010) and future (2021-2060) time periods. Future estimates are based on 11 climate models in from the Coupled Model Intercomparison Phase 5 (CMIP5) experiment. We downloaded data for the Representative concentration path (RCP) 4.5.
Topography				
Elevation	Elevation is associated with temperature, moisture, and seasonality gradients.	Higher = Better (Stark & Fridley 2022), Higher = greater potential drought refugia (Cartwright 2018)	Digital Elevation Model (DEM) https://databasin.org/datasets/3cf598b2d67b4f9f8e3ff47fd5b5ae37/	Calculated as distance above sea level in meters. Supplied by USGS at 90 m resolution.
Slope	Used to gauge exposure to solar energy.	South-facing = Worse	DEM; Cartwright 2018	=Change in vertical distance/Change in horizonal distance. Calculated from DEM using ArcGIS surface statistics.

Ruggedness Index	A measure of local topographic diversity.	Higher = Better	Digital Elevation Model (DEM) https://databasin.org/datasets/3cf598b2d67b4f9f8e3ff47fd5b5ae37/	The Ruggedness Index is the mean difference in elevation between a central pixel and its surrounding cells. It is calculated from the DEM layer (~90m resolution) for 3x3, 9x9 moving windows.
Aspect (radians)	Used as a proxy for solar insolation, evaporative demand, and protection from wind/desiccation.	Context-specific	DEM; Haire et al. 2022	=the direction from the highest point to the lowest point that a pixel faces. This measure is calculated as a degree where 0, 360 = North, 60=East, 180=South, and 240=West.. Calculated from DEM using ArcGIS surface statistics.
Aspect (linear)	Used as a proxy for solar insolation, evaporative demand, and protection from wind/desiccation.	Context-specific	DEM; Haire et al. 2022	=A version of aspect often used in modeling where the radial calculation causes issues. Is generated by multiplying the number of degrees by sind/180.
Derived Topographic				
Landform	A total of 498 unique geomorphon patterns (i.e., representations of the landscape based on elevation differences within the surrounding area of a target cell) are classified into 10 common landform types: flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley, and pit).	Context-specific	DEM and derivatives; Jasiewicz & Stepiski 2012; AdaptWest, https://adaptwest.databasin.org/	Calculated using DEM and Surface Parameters tool in spatial analyst or comparable Geographic Information System (GIS) toolset. Also available as part of the landfacet analysis of AdaptWest.
Catchment Area	Area of that contributes to water accumulation at a given location.		Digital Elevation Model (DEM) https://databasin.org/datasets/3cf598b2d67b4f9f8e3ff47fd5b5ae37/	Measured in m^2 and calculated based on a DEM and derived variables such as slope.
Curve	The overall curvature of the Earth's surface. Proxy for solar radiation and protection from wind/desiccation.	Concave = Better	Digital Elevation Model (DEM) https://databasin.org/datasets/3cf598b2d67b4f9f8e3ff47fd5b5ae37/	Calculated using DEM and Surface Parameters tool in spatial analyst or comparable Geographic Information System (GIS) toolset.

Mean Elevation	Average elevation over a given distance on the landscape.	Higher = Better	Digital Elevation Model (DEM) https://databasin.org/datasets/3cf598b2d67b4f9f8e3ff47fd5b5ae37/	Calculated using a 3x3 cell moving window using focal statistics in a GIS.
Topographic Indices				
Heat Load Index (HLI)	A direct measure of incident radiation.	Lower = Better	Carroll et al. 2017	Carroll et al. (2017) provides HLI in 3 bins: warm (>0.24), neutral, and cool (=<0.223). Calculated using a DEM. Calculated at 100m resolution.
Terrain Ruggedness Index (TRI)	TRI is defined as the mean difference in elevation between a central pixel and its surrounding cells.	Higher = Better	Ackerley et al. 2020	Calculated using a DEM and the TRI Tool in a GIS.
Northness	Represents exposure to incident radiation; more northerly sites are exposed to less incident radiation.	Presence = Better	DEM derived	=cosine of aspect in radians. Gives a value in range of -1 (southward) to 1 (northward). 0 is either east or west.
Eastness	Used in combination with Northness in some analyses of topographic diversity	Context-specific	DEM derived	=sine of aspect in radians. Gives a value in range of -1 (westward) to 1 (eastward). 0 is either north or south
Topographic Position Index (TPI)*	Index based on curvature of the Earth's surface. Proxy for solar radiation and protection from wind/desiccation.	Lower = Better	DEM derived	TPI = difference between elevation of focal cell and mean elevation of surrounding cells. Calculated from DEM using TPI command from the Arc_Hydro_tools_Pro toolbox or similar GIS tool.
Compound Topographic Index (CTI)/Topographic Wetness Index (TWI)/Topographic Convergence Index (TCI)	Family o f hydrological-based indices (sometimes also referred to as a steady state wetness index), these metrics describe the tendency for water to accumulate in an area.	Higher = Better	https://edna.usgs. gov/; Cartwright 2018; Gsech et al. 2002; Stark and Fridley 2022	Calculated as a function of slope and the upstream contributing area to a given point on the landscape. = ln (contributing area/slope angle). TCI can be calculated using the r.topidx routine in GRASS or a similar routine in another GIS (Fridley 2009). Index ranges from -90 to +90.

Slope + Aspect (Southness)	Index used to measure relative exposure to solar radiation.	Lower = Better	Ackerley et al. 2020	Southness = -cos(aspect)Xsin(slope). Variable ranges from –1 to 1 for vertical north-facing and south-facing slopes, respectively, and 0 for a flat site.
Vector Ruggedness Index (VRI)	Measures terrain ruggedness as the variation in the three-dimensional orientation of grid cells within a neighborhood. Slope and aspect are captured into a single measure and used to decouple terrain ruggedness from just slope or elevation.	Higher = Better	Digital Elevation Model (DEM) https://databasin.org/datasets/3cf598b2d67b4f9f8e3ff47fd5b5ae37/	Calculated from DEM using Spatial Analysis tools in a GIS.
Standard Deviation of Slope	Topographic measure of ruggedosity. Represents the variation in slope within the identified spatial unit.	Higher = Better	Digital Elevation Model (DEM) https://databasin.org/datasets/3cf598b2d67b4f9f8e3ff47fd5b5ae37/	Standard deviation of slope in degrees or percent rise across 3x3 or 9x9 cell areas
Land Cover Pattern/Landforms				
Topofacet Layer	Composite index created to represent topographic diversity.	Higher = Better	Carroll et al. 2017	= (Landform + HLI + Elevation). Calculated at 100m resolution.
Facet ID Values	Composite index created to represent topographic diversity.	Higher = Better	Carroll et al. 2017	= ((Landform + HLI + Elevation)*100 + Soil Order). Calculated at 100m resolution.
Convergent Features	Topographic features (such as catchments, valleys, headwaters, and canyons) that indicate the presence of surface water (more is better). This variable is reflective of water accumulation/protection from wind and desiccation/lower evaporative demand (Dobrowski 2011). Presence = greater potential for a site to serve as a temperature refugia (Estevo et al. 2022) or drought refugia.	Presence = Better	National Hydrological Dataset (NHD). https://www.usgs.gov/national-hydrography/access-national-hydrography-products	See topographic list for representation

Presence of Ecotones[a]	Ecotones are areas of transition between vegetation or ecosystem types.	Presence = Greater potential for presence of drought refugia	LANDFIRE (https://www.landfire.gov/); other vegetation covers	Ecotones can be calculated in a variety of ways. Calculated as linear meters of shared border or edge that represent boundary between vegetation or ecosystem types. This metric has not yet been calculated pending discussions of how vegetation will be used in this analysis.
Distance to Ecotone (e.g.. Fir)[a]	Ecotones are areas of transition between vegetation or ecosystem types.	Less = Better	LANDFIRE (https://www.landfire.gov/); other vegetation covers	This can be calculated in a variety of ways from landcover data provided by LANDFIRE and other sources. Calculated as distance (meters) from a border that distinguished the boundary between vegetation types. This metric has not yet been calculated pending discussions of how vegetation will be used in this analysis.
Percent Cover (e.g., Forest)[a]	Percent of an area that has a given vegetation type. This may be generic categories such as trees, shrubs or herbaceous ground cover or may be more specific to vegetative communities (e.g. Conifer Forest) or species (e.g. Ponderosa Pine)	More = Better	LANDFIRE (https://www.landfire.gov/); other vegetation covers	This can be calculated in a variety of ways using zonal statistic tools, overlay or extract in a GIS . This metric has not yet been calculated pending discussions of how vegetation will be used in this analysis.
Stream Distance	Distance to nearest perennial stream. Areas nearer to streams experience greater buffering from local temperature change.	Greater = Worse	National Hydrological Dataset (NHD). https://www.usgs.gov/national-hydrography/access-national-hydrography-products	Distance to stream in meters.
Topographic Diversity				

Aspect Diversity		Higher = Better	Aspect categorized into North, Northeast, East, Southeast, South, Southwest, West, Nortwest	Apply Simpson Diversity index or Shannon Index to categories.
Elevational Diversity		Higher = Better	Carroll et al. 2017; Malakoutinakhah et al. 2018	Following Carroll et al., 2017, we grouped raw elevation data into bins for each 100m. We then estimated Shannon and Simpson indices for binned elevation values for a 3x3 and 9x9 window (~300m^2 and 1km^{2,} respectively). Analysis based on data provided by Carroll et al. (2017) provides elevational diversity at and 1, 3, and 9km resolutions
HLI Diversity		Higher = Better	Carroll et al. 2018	Apply Simpson Diversity index or Gini-Simpson Index to binned HLI values (bins = <0.25, -.25-0.5, >0.5).
Land Facet Diversity		Higher = Better	Carroll et al. 2017; Stalberg et al. 2018	Land-facet diversity is available for 10-km pixel data and is calculated using the Gini-Simpson index on the following two underlying datasets: Facet ID Values = ((Landform + HLI + Elevation)*100 + Soil Order) or Topofacet Values = (Landform + HLI + Elevation)
Topographic Diversity		Higher = Better	Malakoutinakhah et al. 2018	
Soils				
Percent Soil Bulk Density (SBD), 1m	Dry weight of soil divided by its volume. Volume includes volume of soil particles and of pores among soil particles. Lower SBD is associated with higher porosity, which in turn relates to soil water holding capacity (Cartwright 2018); Higher SBD was associated with greater drought sensitivity (Cartwright et al. 2020).	Lower = Better	Available from Soils data- a variety of derived sources (primary source is the Natural Resources Conservation Service (NRCS) U.S. Soils database: https://databasin.org/datasets/de1a45d142f34bbca8010903eef966d9/	Typically measured as g/cm3.

Soil Water Storage/	Total amount of water that can be stored in local soil in the plant root zone.	Higher = Greater potential to constitute drought refugia	Cartwright et al. 2018; Schlaepfer, Andrews, and Bradford 2022 (30km)	Total soil water storage is the amount of water that can be stored per soil volume. Typically expressed as a percentage. Schlaepfer et al. 2022 provide processed soil climate data at 10km resolution produced using SOILWAT2 ecosystem water balance model.
Soil Water Availability (SWA)/Available Water Capacity (AWC)/Available Soil Moisture	. SWA is total amount of water that can be stored in local soil in the plant root zone. It is an indicator of a soil's ability to retain water. Available Soil Moisture refers to the simulated Soil Water Availability (SWA) metric	Higher = Better	Available from Soils data- a variety of derived sources (primary source is the Natural Resources Conservation Service (NRCS) U.S. Soils database: https://databasin.org/datasets/de1a45d142f34bbca8010903eef966d9/	Schlaepfer et al. 2022 calculated a daily summed value across soil layers in 0-20, 20-100, and 0-100 cm of soil water content held at a potential > -3.9 MPa. Schlaepfer et al. 2022 provide processed soil climate data at 10km resolution produced using SOILWAT2 ecosystem water balance model. This variable is available at annual and quarterly intervals for historic (1970-2010) and future (2021-2060) time periods. Future estimates are based on 11 climate models in from the Coupled Model Intercomparison Phase 5 (CMIP5) experiment. We downloaded data for the Representative concentration path (RCP) 4.5.
Mean Duration Dry Soil Intervals	Annual mean length of dry soil interval (DSI) where all soil layers at 0–100 cm depth have soil water potential < −1.5 MPa	Lower = Better	Schlaepfer, Andrews, and Bradford 2022; Chambers et al. 2023 ()	Schlaepfer et al. 2022 provide processed soil climate data at 10km resolution produced using SOILWAT2 ecosystem water balance model. Provided at 10 and 30km resolution. This variable is available at annual and quarterly intervals for historic (1970-2010) and future (2021-2060) time periods. Future estimates are based on 11 climate models in from the Coupled Model Intercomparison Phase 5 (CMIP5) experiment. We downloaded data for the Representative concentration path (RCP) 4.5.

Presence of Shallow or Finer Textured Soils	Relates to soil moisture holding capacity; more fine soil = less soil moisture holding capacity. Shallower soils, less root zone, less moisture holding capacity.	More = Worse	Available from Soils data- a variety of derived sources (primary source is the Natural Resources Conservation Service (NRCS) U.S. Soils database: https://databasin.org/datasets/de1a45d142f34bbca8010903eef966d9/	Particle size analysis determines the relative proportions of sand, silt and clay in a soil, which is then used to classify soil texture. Finer textures have more clay. Soil depth is calculated as number of inches to layer that retards root development. Soils with a depth less than 20 inches to a layer that retards root development are considered shallow.
Disturbances				
Development Threat to HUC12		Lower = Better	Forest to Faucet analysis, https://www.fs.usda.gov/research/treesearch/63723	Data, summarized as a percent of HUC12 subwatershed unit likely to experience threat due to development, are available for mid and end of century under low and high representative concentration paths (4.5, 8.5)
Water Yield Threat to HUC12		Lower = Better	Forest to Faucet analysis, https://www.fs.usda.gov/research/treesearch/63723	Data, summarized as a percent of HUC12 subwatershed unit likely to experience threats that reduce water yield, are available for mid and end of century under low and high representative concentration paths (4.5, 8.5)
Percent Forest Cover	Canopy closure is associated with less fluctuation in temperature and soil moisture conditions. Greater Forest Cover = lower temp; more=better temperature stability in summer and autumn and annually (Estevo et al. 2022)	Higher = Better	LANDFIRE (https://www.landfire.gov/); Forest to Faucet analysis, https://www.fs.usda.gov/research/treesearch/63723	Usually calculated as proportion of Forest, Forest type or dominant species per unit of area. Forest to Faucet analysis summarizes values by HUC12 units. Forest Cover is estimated from National Land Cover Database (NLCD) (USGS 2019) (https://www.mrlc.gov/data)
Percent Natural Cover	Sometimes considered in analysis of refugia as an indicator of potential habitat	Higher = Better	LANDFIRE (https://www.landfire.gov/); Forest to Faucet analysis, https://www.fs.usda.gov/research/treesearch/63723	Forest to Faucet analysis summarizes values by HUC12 units. Percent natural cover is estimated from National Land Cover Database (NLCD) (USGS 2019) (https://www.mrlc.gov/data)

*See Data Catalogue for more information about specific data sources used.

**Current climate conditions are available at a variety of spatial (Extrapolated from weather stations, modeled at 12km, 4km and downscaled to 1km and 90m) and temporal (daily, weekly, monthly) scales. To create estimates for New Mexico and because we anticipated generating historic and future climate variables, we used data available from the WorldCLIME project. This data is generated at a 1km scale and includes observed (1970-2020) and future projected conditions under 17 General Circulation Models run as part of the CMIP5.

[a] This metric has not been produced at the time of this draft version.

[b] A diversity index quantifies the number of species within a sample and how evenly individuals are distributed among species. Shannon and Simpson Diversity Indices are commonly used to measures species diversity and also have been applied to a wide variety of purposes where more information on the composition and evenness of constituent elements is needed. The Simpson's index is calculated as

$$D = Sum\left(\frac{ni(ni-1)}{N(N-1)}\right)$$

where n is the number of individuals in species i and N is the total number of species in the sample. The Shannon's Index (or Shannon-Weiner) is calculated as

$$H' = \frac{(N * \ln(N)) - Sum\big((ni * \ln(ni))\big)}{N}$$

Where N is the total number of species and ni is the number of individuals in species i. The Simpson index is a weighted arithmetic mean of the proportional abundance of species and represents the probability that two individuals randomly selected from a sample will belong to the same species. Simpson's D ranges from 0 to 1, with 0 representing infinite diversity and 1 representing no diversity. In comparison, the S-W diversity index is more sensitive to the number of species in a sample and so is biased toward measuring species richness. The Shannon's Index usually ranges between 1.5 and 3.5 with higher values indicating greater species richness and greater species evenness.

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