NEW MEXICO PUBLIC LANDS AND THEIR SIGNIFICANCE TO CLIMATE CHANGE ADAPTATION AND MITIGATION:

IDENTIFYING PRIORITIES FOR CONSERVATION AND STEWARDSHIP

EcoAdapt™
Meeting the challenges of climate change

December 2022

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For more information about this report, please contact Laura Hilberg (Laura.Hilberg@EcoAdapt.org).

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Executive Summary

Scientists and policymakers are calling for the conservation of 30% of the world's lands and waters by 2030 in order to protect global biodiversity and critical ecosystem services, including those necessary for climate change adaptation and mitigation. This goal, known as the "30x30 initiative", is supported by President Biden at the national level as well as by many state governments. These include New Mexico, where the percent of protected lands managed primarily for biodiversity lags behind national levels (6.1% in New Mexico compared to 12.6% nationally) despite the relatively high proportion of public lands and rich biodiversity present in the state.

The purpose of this study was to evaluate the climate change adaptation and mitigation value of 5.9 million acres of federally-owned public lands in New Mexico that have been identified as potential priorities for additional protection as part of the 30x30 initiative. In order to accomplish this, we assessed five different indicators of climate change adaptation and mitigation: biodiversity, connectivity, site resilience, carbon storage, and greenhouse gas emissions associated with unleased fossil fuels. For each of these indicators, we identified the 25% of the study area (roughly 1.5 million acres) that represents the highest priority for additional protection based on the highest scores for that indicator. Then we overlaid these priority areas to better understand which locations might make the greatest contribution to climate adaptation and mitigation objectives across across multiple indicators.

Key Findings

Protected areas have the potential to contribute significantly to ecosystem adaptation to climate change (*1*–*3*) by maintaining landscape-scale ecological processes and housing larger populations of sensitive species that increase the potential for local genetic adaptation (*3*, *4*) and are less vulnerable to extirpation (*5*).

- Protected areas represent a highly effective strategy to protect existing biodiversity (*5*–*7*), particularly when they are strategically placed to increase representation of intact, high-quality habitats across a range of environmental conditions (*2*, *7*, *8*). Within the study area, the 1.7 million acres with the highest presence of range-restricted imperiled species accounts for 11% of the total state biodiversity score despite accounting for only 2% of the land area. This suggests that there is high potential for targeted protection of sites with the highest value for rare species and isolated populations, which are known to be particularly vulnerable to climate change (*9*, *10*).
- Protected areas that significantly increase landscape connectivity and represent a range of environmental conditions increase species movement (*11*) and gene flow (*12*), reducing the risk of extirpation in isolated populations (*13*, *14*) and facilitating access to suitable habitat patches that can act as "stepping stones" to facilitate range shifts (*1*, *15*–*17*). Portions of the study area where barriers are low and species are able to freely move across large areas primarily lie in the Chihuahuan Desert and Arizona/New Mexico Mountains ecoregions, while more concentrated movement corridors are found in

riparian areas. Expanding protection to include lands with the highest potential for maintaining species movement are likely to minimize biodiversity loss across larger spatial scales while simultaneously supporting shifts in species distribution in response to climate change (*2*, *15*, *18*–*20*).

- Resilient protected area networks are able to maintain the conditions necessary to sustain biodiversity and ecosystem processes as climate change occurs (*21*–*23*), and typically include intact, high-quality ecosystems in areas with high topographic complexity and geophysical diversity, as well as in high-elevation areas, riparian zones, and other sites with permanent sources of surface water (*24*–*27*). Within the study area, the most resilient sites are disproportionately located in the Arizona/New Mexico Mountains ecoregion, but many are also found in the Chihuahuan Desert in the southwest corner of the state. Strengthening protection for these sites is likely to result in the conservation of important climate refugia (i.e., areas that are buffered from exposure to rapid changes and climate extremes) that facilitate the persistence of sensitive species, buying time for adaptation over longer time scales (*17*, *28*).

Protected areas can also play an important role in climate mitigation efforts by preventing the degradation and loss of ecosystems that sequester and store carbon (*29*–*32*), as well as by limiting the extraction of fossil fuels that are associated with greenhouse gas emissions (*33*, *34*).

- Protection of intact ecosystems supports continued carbon sequestration and storage within plants and soils by preventing disturbances and land-use change that negatively impact the ecosystem processes that support these functions (*29*–*32*). By the end of the century, the study area has the potential to hold carbon stocks of 210.1 to 240.6 million metric tons of carbon, with the low end of that range occurring under the hottest, driest future scenarios. Within the study area, the amount of carbon stored per acre will be highest in the Southern Rockies ecoregion where vegetation is dominated by relatively dense montane forests, with an average density of 87 metric tons carbon per acre. Expanding protected area networks in order to maximize carbon stocks would benefit from preventing the degradation and loss of these areas to ensure continued carbon sequestration over the coming decades.
- Keeping oil, gas, and coal in the ground has the potential to significantly contribute to climate mitigation targets by preventing greenhouse gas emissions associated with fossil fuel production and end-use consumption (*35*, *36*). An estimated 2,752 million barrels of crude oil, 3,075 billion cubic feet of natural gas, and 403 million short tons of coal may remain underground in unleased portions of the study area. Together, these are associated with lifecycle greenhouse gas emissions of 2,943 million metric tons of carbon dioxide equivalent, an amount is equivalent to 5.3 months of greenhouse gas emission for the entire U.S. at 2018 levels (*37*). Strengthening protection with designations that prohibit new lease sales and fossil fuel extraction (i.e., wilderness designation) would help ensure that these fuels are permanently sequestered underground, preventing additional greenhouse gasses from entering the atmosphere.

Introduction

The 30x30 initiative, put forth by the United Nations Convention on Biological Diversity, calls for conserving 30% of the world's terrestrial and marine ecosystems by 2030 in order to protect global biodiversity and ecosystem services, including those critical for both adapting to and mitigating climate change (*38*). The United States is among many countries in support of the initiative, which was formalized on January 27, 2021 when Biden signed Executive Order 14008 "Tackling the Climate Crisis at Home and Abroad" that included a commitment to conserving at least 30% of U.S. lands and waters by 2030. While none of the 30x30 commitments have yet defined the level of protection that will count towards these goals, most existing studies evaluating 30x30 goals (*39*–*41*) refer to GAP status 1 and 2 lands from the Protected Areas Database of the United States (PAD-US), which are protected with the primary goal of managing for biodiversity. Currently only 12.6% of the U.S. land area are categorized as GAP 1 or 2, an area equivalent to 306.9 million acres (*42*). An additional 17.3% (421.2 million acres) is protected from conversion but open to multiple uses (GAP status 3), which may include resource extraction such as logging and mining (*42*). Generally, GAP 3 protection is assumed to be inadequate for meeting 30x30 conservation goals due to the ecosystem degradation and loss of biodiversity that can occur as a result of activities such as these.

Based on the PAD-US GAP categories, an additional 425 million acres of land must be granted GAP 1 or 2 levels of protection by 2030 in order to meet the 30x30 conservation goal at a national level. This could occur through a combination of designating new protected areas such as wilderness areas, national parks, wildlife refuges, and state parks or preserves, or by strengthening the status of existing protected areas that are currently not being managed primarily for biodiversity (e.g., GAP status 3 lands). Many of these areas are vulnerable to loss or downgrading of their protected status as a result of political pressure often related to use of natural resources (*43*, *44*), such as occurred in 2017 when a review of National Monuments ordered by the Trump Administration threatened New Mexico's Organ Mountains Desert Peaks and Rio Grande del Norte National Monuments (*45*). Thus, strengthening the protected status of existing protected areas represents an important strategy to prevent the future degradation of intact, high-quality ecosystems. In particular, wilderness designation requires support from Congress for both addition and removal of lands from the National Wilderness Preservation System, making it the strongest and most permanent level of conservation protection available in the United States (*46*).

Many state governments have also committed to 30x30 goals that align with international and federal targets. This includes New Mexico, where in August 2021 Governor Michelle Lujan Grisham signed an executive order titled "Protecting New Mexico's Lands, Watersheds, Wildlife, and Natural Heritage" (Executive Order 2021-052), which calls for New Mexico to protect 30% of its land and waters by the year 2030. Currently, only 6.1% of the state (4.8 million acres) is protected under GAP 1 or 2 status, meaning that an additional 18.6 million acres would need to be added to achieve statewide 30x30 goals (*42*). An additional 25.5% (19.8 million acres) of undeveloped land is currently managed under GAP status 3 (*42*), highlighting ample opportunities to strengthen and extend the existing protected area network.

Climate change adaptation and mitigation benefits of 30x30 goals

Protected area designation represents a well-established and highly effective strategy to protect existing biodiversity (*5*–*7*, *47*), particularly when sites are strategically located to maximize connectivity and representation of ecosystem niches and habitat types for a range of species (*7*, *8*, *18*, *48*, *49*). However, climate change is already impacting biodiversity within protected areas, and climate-driven losses of native species and ecosystem functioning within protected areas are expected to continue into the future (*15*, *20*, *50*, *51*). As a result, it is critical that efforts to increase protected area networks prioritize sites that not only safeguard biodiversity and meet other conservation objectives (*9*, *39*, *40*, *52*, *53*), but also contribute to ecosystem adaptation to climate change as well as climate change mitigation efforts (*1*, *18*, *39*, *40*, *54*, *55*). To date, many of the areas with the greatest potential to support climate change adaptation and mitigation remain unprotected, including those that could serve as climate refugia, provide corridors that facilitate climate-driven range shifts, and/or sequester and store large amounts of carbon (*20*, *25*, *39*, *40*). Ensuring that these sites are protected from land-use conversion and human activities that result in degradation of these services will allow protected areas to play an important role in ecosystem adaptation to climate change as well as efforts to meet climate mitigation targets.

The goal of this study was to assess the potential climate change adaptation and mitigation value of New Mexico public lands identified by New Mexico Wild as potential candidates for additional protection. To accomplish this, we identified or created datasets to represent several critical indicators of climate change adaptation and mitigation across the landscape, including biodiversity, connectivity, landscape resilience, carbon sequestration and storage, and potential greenhouse gas emissions associated with unleased fossil fuels. Each of these five indicators was used to evaluate the relative value of protected areas considered in the study, and the top 25% of the study area for each indicator was overlaid to identify areas that may represent the highest priorities for additional protection across multiple considerations. The resulting maps and datasets are intended to assist conservation planners, land managers, and advocates in determining where strengthening existing protection of public lands may provide the greatest climate change benefits.

Study Methodology

Study area

The study area was comprised of 5,908,218 acres of federal public lands identified as having high potential for contributing to 30x30 goals (Figure 1), primarily through strengthening of their existing status (i.e., shifting protected areas from GAP 3 into GAP 1 or 2 status) and/or reducing the likelihood that their existing GAP 1–2 status will be lost or downgraded (i.e., by designating additional areas as wilderness). The areas considered include federal lands managed by the Bureau of Land Management, National Park Service, and U.S. Forest Service, and currently designated as Areas of Critical Environmental Concern (ACECs), Inventoried Roadless Areas (IRAs), Lands with Wilderness Characteristics (LWCs), and Wilderness Study

Areas (WSAs). Some additional federal lands identified as having wilderness characteristics through on-the-ground surveys by New Mexico Wild were also included. Although this study focuses exclusively on federally-owned public lands, it should be noted that tribal, state trust, and private lands also play an important role in effective protected area networks (*56*).

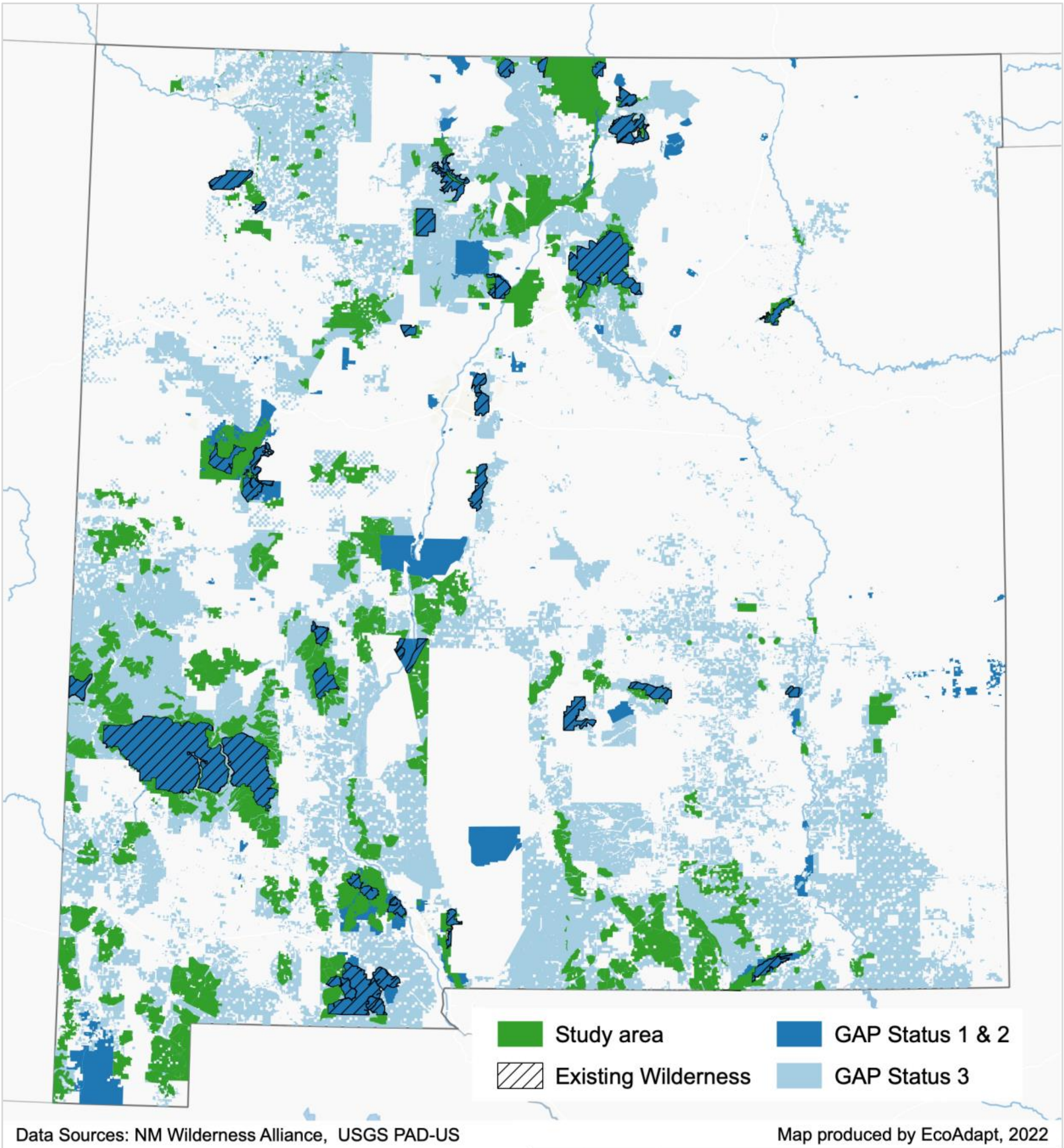

Figure 1. New Mexico study area comprised of federal public lands identified as having high potential for contributing to 30x30 goals (green), compared to GAP 1–2 lands (dark blue) and GAP 3 lands (light blue) that lie outside of the study area. Hatching indicates existing wilderness areas.

Because research on protected area network design has emphasized the importance of adequately representing the full range of ecological systems (*8*, *49*, *57*), we also considered the study area distribution among ecoregions (i.e., areas with similar physiography and landscape features). For this, we utilized the Level III ecoregion map published by the U.S. Environmental Protection Agency, which divides the U.S. into 182 ecoregions (*58*). Eight of the Level III ecoregions overlap a portion of New Mexico: the Arizona/New Mexico Mountains, Arizona/New Mexico Plateau, Chihuahuan Deserts, Colorado Plateau, High Plains, Madrean Archipelago, Southern Rockies, and Southwestern Tablelands (Figure 2; see Appendix A for a description of these ecoregions). Several of these have disproportionately little protected area, with the Colorado Plateau (0.1% of the area in New Mexico protected), Southwestern Tablelands (0.4%) and High Plains (0.7%) ecoregions particularly underrepresented within the existing network (Table 1). Within the 5.9-million-acre study area, the majority of the lands proposed for additional protection lie in the Chihuahuan Desert (31%), Arizona/New Mexico Mountains (30%), and Arizona/New Mexico Plateau (22%) ecoregions (Table 2).

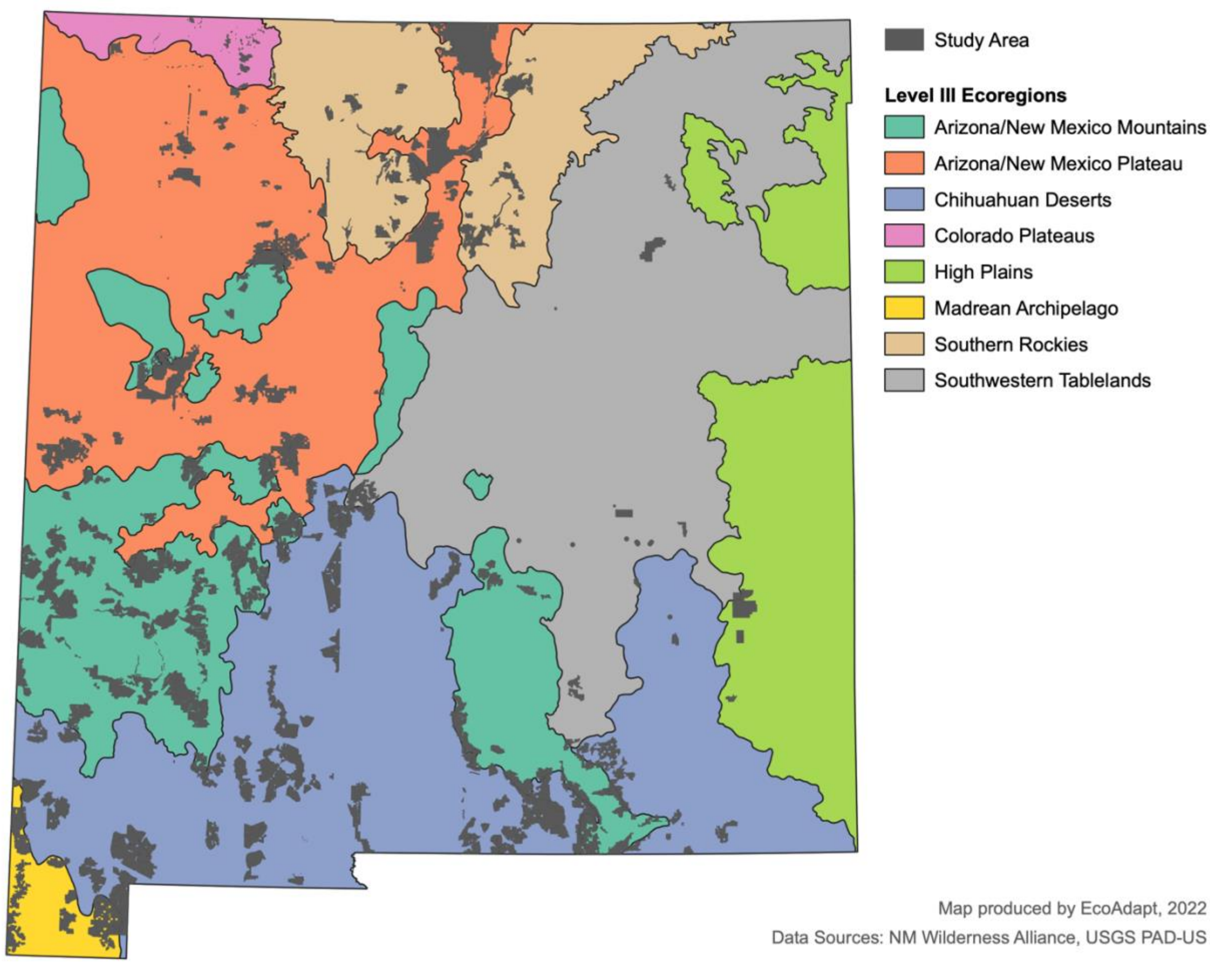

Figure 2. New Mexico study area overlaid on Level III ecoregions, which include the Colorado Plateau, Southern Rockies, Arizona/New Mexico Plateau, Arizona/New Mexico Mountains, Chihuahuan Deserts, Madrean Archipelago, Southwestern Tablelands, and High Plains.

Table 1. Acreage and percent (%) of New Mexico land area protected under GAP status 1 or 2 and GAP status 3 for each Level III Ecoregion, out of a state-wide total area of 77,819,673 acres.

Ecoregion Name	Acres GAP 1–2	% GAP 1–2	Acres GAP 3	% GAP 3
Arizona/New Mexico Mountains	1,441,867	12.5%	5,327,449	46.0%
Arizona/New Mexico Plateau	1,054,011	7.1%	2,669,760	17.9%
Chihuahuan Deserts	1,112,109	6.4%	6,572,826	38.1%
Colorado Plateau	790	0.1%	467,824	47.8%
High Plains	57,258	0.7%	626,515	8.0%
Madrean Archipelago	366,154	34.3%	268,572	25.1%
Southern Rockies	665,472	10.2%	2,415,941	36.9%
Southwestern Tablelands	69,371	0.4%	1,473,285	8.4%
TOTAL	**4,767,034**	**6.1%**	**19,822,223**	**25.5%**

Table 2. Distribution of the study area acreage and percent of the study area in each Level III Ecoregion.

Ecoregion Name	Acres	% Study Area
Arizona/New Mexico Mountains	1,776,689	30.1%
Arizona/New Mexico Plateau	1,322,867	22.4%
Chihuahuan Deserts	1,860,217	31.5%
Colorado Plateau	30,177	0.5%
High Plains	66,186	1.1%
Madrean Archipelago	310,570	5.3%
Southern Rockies	378,780	6.4%
Southwestern Tablelands	162,731	2.8%
TOTAL	**5,908,218**	**100%**

Adaptation indictors

We identified three indicators that provide information about the potential for protected lands across the study area to contribute to ecosystem adaptation to climate change: biodiversity, connectivity, and resilience. To evaluate these, we clipped state-wide datasets to include only the study area, and then we identified the roughly 1.45 million acres with the highest scores for each indicator (25th percentile of the study area). These lands, referred to here as the "Top 25%", represent the portion of the study area where protection is likely to provide the greatest value for conservation of biodiversity, connectivity, or resilient sites, respectively.

Biodiversity

To evaluate biodiversity, we obtained data on range-size rarity from NatureServe's Map of Biodiversity Importance (*53*, *59*), which highlights areas with high potential for species conservation across the U.S. using habitat models for over 2,200 imperiled species including vertebrates (e.g., birds, mammals, amphibians, reptiles, freshwater/anadromous fish), vascular plants, selected aquatic invertebrates (mussels and crayfish), and selected pollinators (bumblebees, butterflies, skippers). Range-size rarity is a metric related to species richness, but is weighted to place greater emphasis on species with small range sizes that are more likely to be endemic, rare, or of significant conservation concern (*53*). Because species that are isolated or have small populations and/or limited distribution tend to be more vulnerable to extirpation as a result of extreme events and environmental changes, including climate change (*10*, *60*), using range-size rarity is considered a good indicator of where protected areas could play a greater role in protecting critical species from climate-driven declines (*9*, *53*). The NatureServe dataset sums the range-size rarity scores of all species that occur within each cell (mapped at 990-meter resolution), calculated as the inverse of the total area mapped as habitat for each of the 2,216 imperiled species considered. Thus, higher values on the map indicate where imperiled species with very small ranges and/or the presence of multiple range-restricted species occur. These areas are likely to represent locations where conservation of biodiversity is particularly critical to avoid loss of these vulnerable species.

Connectivity

To assess the value of protected areas across the study region for connectivity, we utilized the Connectivity and Climate Flow dataset from The Nature Conservancy's (TNC) Resilient and Connected Network analysis (*22*, *23*, *61*), which provides maps to assist in the identification of well-connected, climate-resilient sites representing the full range of geophysical settings. The Connectivity and Climate Flow dataset highlights permeable areas that allow species movement across sites and climate gradients, which would support migration and range shifts in response to climate change. Mapped values range from -3500 to +3500, representing areas that are blocked or have low climate flow (i.e., little movement occurs or species are deflected around impermeable features) to those with diffuse flow (i.e., intact ecosystems that facilitate high levels of dispersed movement that can follow many different pathways), and are mapped at a 30-meter resolution.

Resilience

To evaluate relative resilience across the study area, we used the Resilient Sites dataset, also from TNC's Resilient and Connected Network analysis (*22*, *23*, *61*). In this context, resilience refers to the ability of that location to maintain biodiversity and core ecosystem functioning even as climate change alters the specific species assemblages or vegetation type/structure (*21*). The Resilience score includes microclimate diversity, which is an estimate of number of microclimates created by topography and elevational gradients within a given area (*21*–*23*) and is known to be closely linked to the presence of climate change refugia that facilitate species persistence under changing conditions (*24*, *62*). It also incorporates a metric related to local connectedness, which estimates the degree to which sites are connected by natural cover that make it possible for species to access refugia and respond to changing conditions. Mapped values for the Resilience score also range from -3500 to +3500, described as the amount above or below average compared to other cells within the ecoregion (mapped at a 30-meter resolution). Within this dataset, tribal land results are not publicly available, and so these areas are excluded from the map.

Mitigation indicators

In order to evaluate the contribution of the study area lands to climate mitigation efforts, we conducted two separate analyses to estimate: a) the amount of carbon that would be sequestered (i.e., captured) and stored on these lands by the end of the century, if they remained undisturbed, and b) the amount of oil, gas, and coal resources present on the study area lands and greenhouse gas emissions associated with those resources. As with the adaptation indicators, we also identified the 25% of the study area (roughly 1.45 million acres) where additional protection is likely to result in the greatest value for climate mitigation efforts based on the amount of carbon sequestered and stored in the ecosystem or potential avoided greenhouse gas emissions.

Carbon stocks

To assess the value of protected areas for carbon sequestration and storage, we used a dataset that was produced by the MC2 dynamic vegetation model and published as part of the CONUS Climate Console (*63*), a web mapping application developed by the Conservation Biology Institute for exploring climate projections and simulated impacts. The MC2 model simulates shifts in vegetation and associated changes in ecosystem carbon stocks under future climate conditions at a 2.5 arc-minute (~4 km) spatial resolution (*64*, *65*). MC2 considers soil characteristics, climate conditions (e.g., temperature, precipitation, vapor pressure), and atmospheric CO_2 as well as wildfire and competition for soil moisture and nutrients. Then it simulates interactions between these factors by modeling primary productivity, decomposition, soil respiration, and nutrient release over time to determine the amount of carbon stored within plant and soil carbon pools. Within the CONUS Climate Console, these results are presented as the average total ecosystem carbon per decade (i.e., decadal means) for each potential vegetation class (e.g., conifer forest, cool mixed forest, deciduous forest, woodland/savannah, shrubland/woodland, grassland) expected to occur within the state by the end of the century, though these results do not take into account the modeled impacts of fire suppression on potential vegetation. Results are presented for a suite of 20 models included in the 5th Coupled Model Intercomparison Project (CMIP5) (*66*) that have been downscaled by the Multivariate Adaptive Constructed Analogs (MACA) project (*67*). The models were run using Representative Concentration Pathway 8.5, which is a high-emissions scenario representing a future where greenhouse gas emissions result in global temperature increases of 3.3–5.4°C (*68*).

For this study, we averaged decadal means for the 2070s, 2080s, and 2090s for three of the climate models to arrive at a 30-year time period representing late-century (2070–2099) climate conditions for Total Ecosystem Carbon (g C/m^2), which includes aboveground and belowground herbaceous and woody plant material as well as soil organic carbon. The three climate models we used were CanESM2, GFDL-ESM2M, and IPSL-CM5A-MR, which were chosen for this study because they capture a wide range of potential futures (e.g., 90% of the range for temperature projections among the suite of 20 models and 100% of the range for precipitation projections for the state of New Mexico; Figure 3).[1]

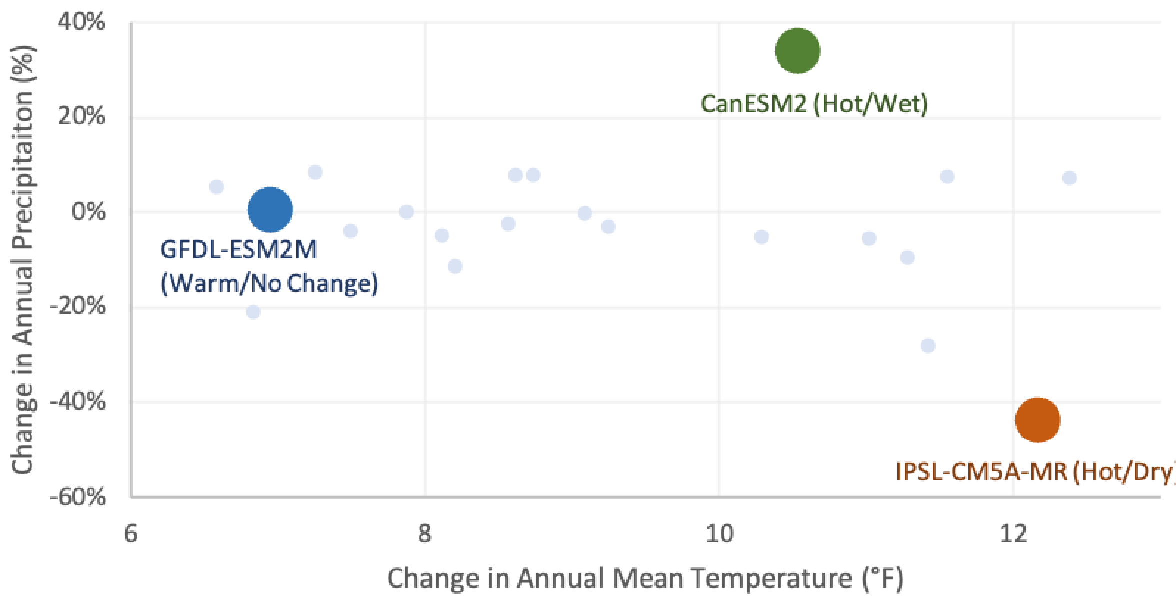

Figure 3. Comparison of change in annual mean temperature (°F) and annual precipitation (%) for the state of New Mexico across the three climate models used in this study, which are GFDL-ESM2M (representing warm temperatures with little to no change in precipitation), CanESM2 (representing large increases in both temperature and precipitation), and IPSL-CM5A-MR (representing hotter, drier conditions). Light blue dots represent the MACA-downscaled models not selected for this study, showing that the selected models span almost the entire range of potential conditions (wettest to driest; lower to higher temperature increases).

Greenhouse gas emissions associated with unleased fossil fuels

We used publicly-available data on fossil fuel resources and typical production in the region to estimate the total amount of unleased crude oil, natural gas, and coal that may remain in the study area, and then calculated the greenhouse gas emissions that would occur if all of those areas were leased and fully developed in the future. For crude oil and natural gas, we calculated the amount of the study area overlapping major basins and plays (*69–71*), and then used the average well spacing (*72*) and average Estimated Ultimate Recovery (EUR) for each well (*73*) to determine potential production. For coal, we determined the acreage of the study area that overlapped with each coalfield (*74*) and assigned the same proportion of remaining recoverable resources (*75*) to those parcels, assuming the resources were evenly distributed across the

[1] Projection ranges used were from the Scatterplot Visualization of Future Projections online tool on the MACA website, accessed on September 27, 2022 at https://climate.northwestknowledge.net/MACA/vis_scatterplot.php.

coalfield. Wherever possible, we improved the accuracy of production and remaining resource estimates by including parameters that were location-specific and/or that reflected the economic feasibility of energy development. For all fossil fuels, we then used greenhouse gas emission factors published by the Bureau of Land Management (*73*), which account for both direct emissions (resulting from exploration, development, and production) and indirect emissions (from processing/refinement, transportation/distribution, and combustion during end use). Greenhouse gas emissions are reported in units of carbon dioxide equivalent (CO_2e) based on 100-year global warming potential (a measure of how much heat a greenhouse gas traps in the atmosphere relative to carbon dioxide) for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

It is important to note that this analysis represents an estimate of greenhouse gases associated with fossil fuels that would remain sequestered underground if protected area status was sufficiently strong to prevent these activities (i.e., if they were designated as wilderness areas). However, it does not represent an accurate estimate of 'avoided greenhouse gas emissions' because this study was unable to account for many other factors that might prevent fossil fuel resources from being extracted and used even in the absence of protected status. These factors include multiple use conflicts (e.g., the inability to extract oil and gas resources where a coal mine is placed), land use restrictions (e.g., the presence of cultural sites or protected species), and economic and technological constraints, among other factors.

See Appendix B for a full description of the methods used for this analysis, including data sources and significant assumptions/sources of uncertainty.

Results and Discussion

Contribution of study area to ecosystem adaptation to climate change

Protected areas generally represent relatively intact, high-quality ecosystems, and it is widely acknowledged that they are an effective strategy for preserving biodiversity and large-scale ecosystem functioning that supports natural systems and human communities worldwide (*3*, *5*, *47*, *76*–*78*). Globally, intact ecosystems are being rapidly lost (*79*, *80*) and biodiversity continues to decline (*81*, *82*), increasing the urgent need for efforts to strengthen and expand existing protected area networks to prevent the irreversible loss of critical benefits such as support of habitat and movement corridors for endemic and/or rare species, protection of freshwater supplies and quality, carbon sequestration, and other benefits (*3*, *5*, *18*, *41*, *79*). Climate change makes these efforts even more important, as ecologically-intact protected areas that have high connectivity and represent a wide range of environmental conditions are likely to support adaptation within individual species, communities, and/or ecosystems (*2*, *3*, *18*, *77*, *78*).

Biodiversity

New Mexico is a state rich in biodiversity, due to the large climatic and elevational gradients, complex topography, and varied substrates that support hundreds of rare species and 90 state endemics (i.e., species found only within the state) (*83*, *84*). However, this biodiversity is not evenly distributed across the state; rather, it tends to be concentrated in areas such as riparian corridors and the Madrean sky islands (*53*, *59*). Nationally, a significant proportion of imperiled species (i.e., species with declining populations that are now at risk of extinction) occur outside of protected areas managed primarily for biodiversity (e.g., GAP status 1 or 2) (*9*, *39*, *52*, *53*), and this pattern holds true in many areas of New Mexico as well (*53*).

The project study area captures a disproportionate amount of statewide imperiled species richness (as measured by range-size rarity, which places greater weight on the presence of range-restricted species). Specifically, the study area captures 11% of the total range-size rarity score for New Mexico despite accounting for only 7% of the state area (about 5.8 million acres; Figure 4). Furthermore, the vast majority of the range-restricted imperiled species in the study area (99%) are found in just over a quarter of the study area acreage (1.7 million acres), representing 2% of the state (Figure 5). Within the top 25%, 1.1 million acres lies in the Arizona/New Mexico Mountains ecoregion, particularly in the western part of the state around Gila Wilderness and the smaller Blue Range and Apache Kid Wilderness areas.

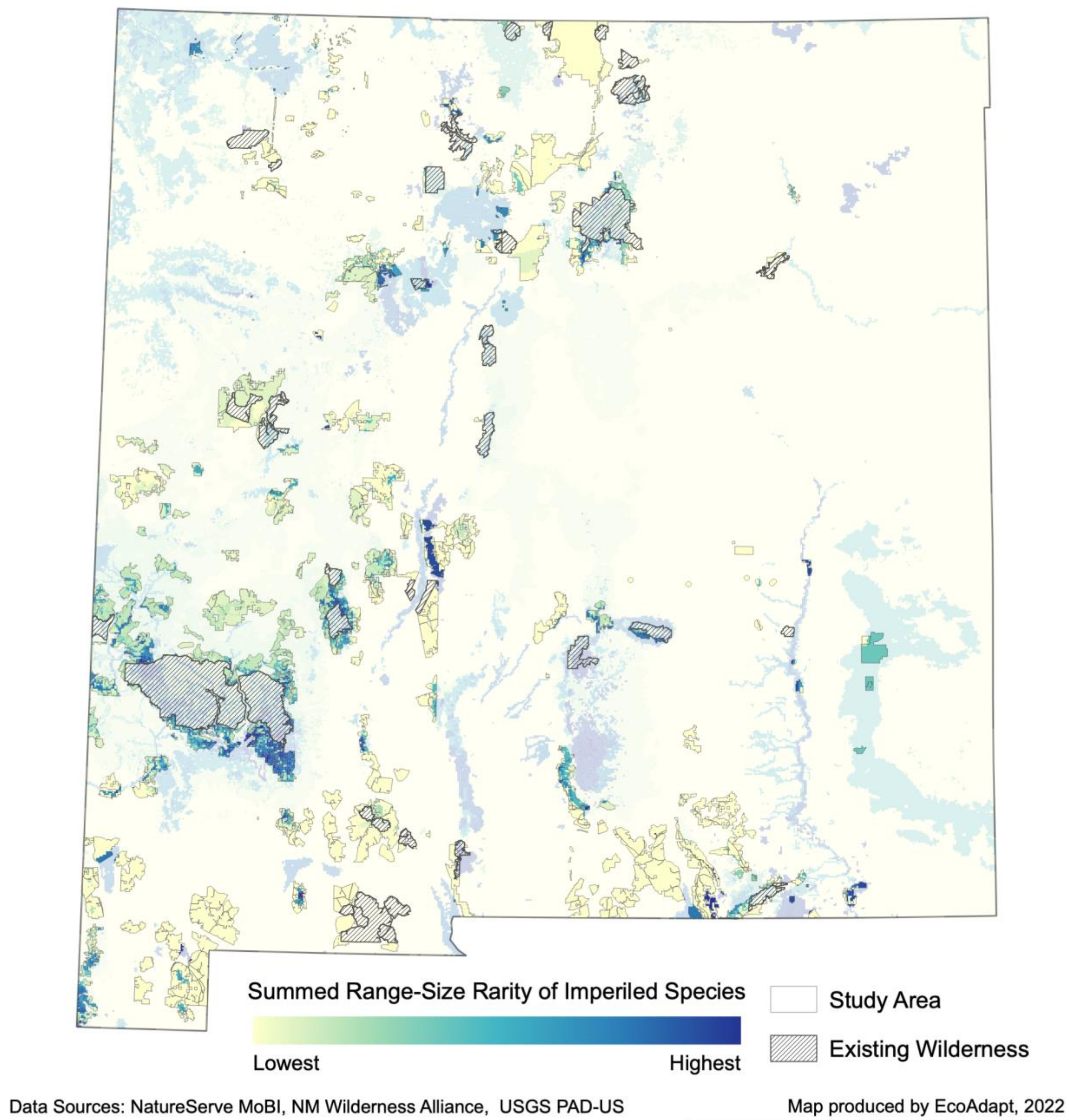

Figure 4. Range-size rarity of imperiled species in New Mexico, highlighting values for range-restricted species within the project study area.

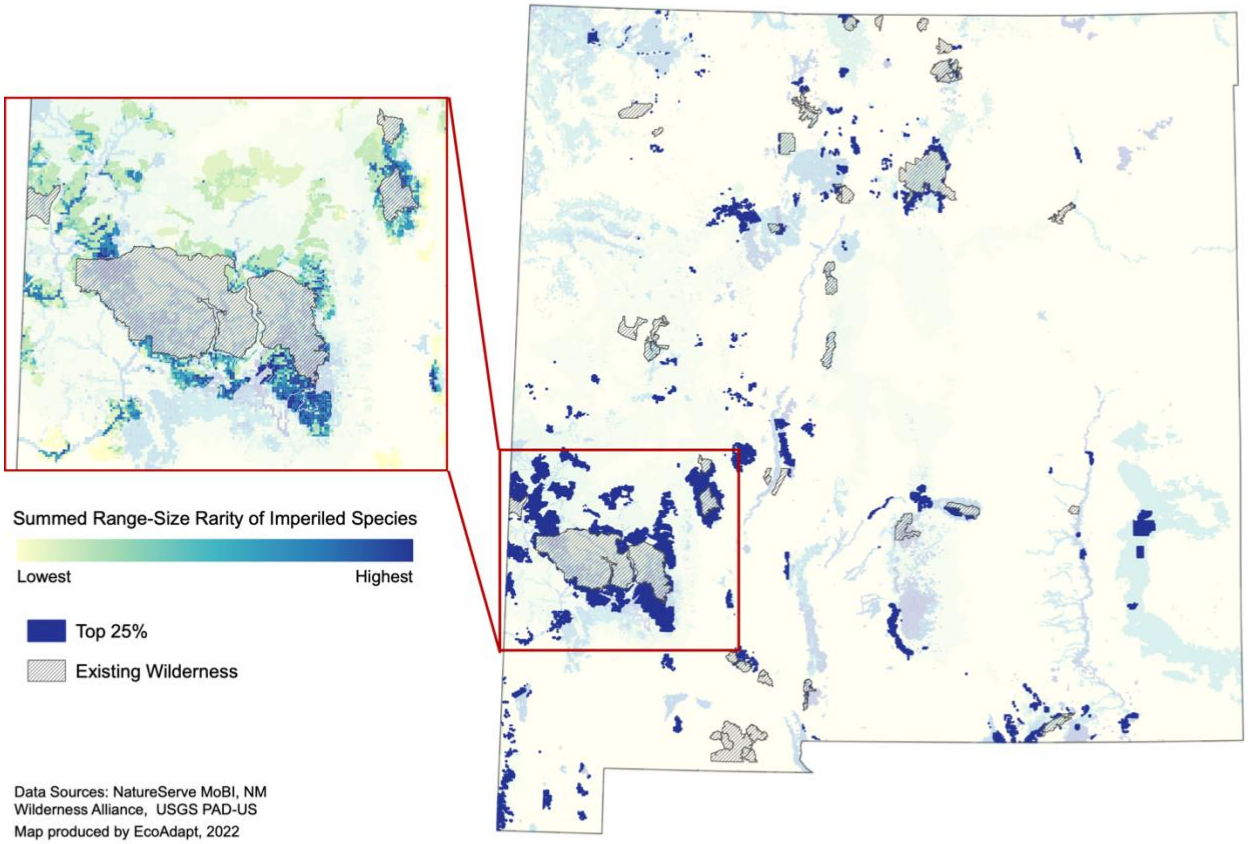

Figure 5. Twenty-five percent (25%) of the study area with the highest score for range-size rarity, representing 11% of the total range-size rarity score for the state within 2% of the land area. Inset box displays a more detailed view of the map in Figure 4 for the area where the greatest concentration of that top 25% is found, in the Arizona/New Mexico Mountains ecoregion.

It is well known that the presence of protected areas reduces extinction risk (*5*, *47*) and is associated with increased species richness (*6*, *7*). Even as climate change drives additional biodiversity loss and shifts in species distribution and community composition (*20*, *51*, *81*, *85*), protected areas are likely to play a critical role in facilitating species persistence (*1*, *6*, *7*, *47*), particularly for rare species or isolated populations that are particularly vulnerable to extreme events and stressors associated with both human activities and climate change (*9*, *10*). They may also play an important role in facilitating range shifts by providing high-quality habitat for colonization by species expanding into new regions (*1*). These results suggest that the study area represents significant opportunities for conservation of biodiversity in the context of climate change, due to the concentration of range-restricted species within the protected areas considered here. Specifically, focusing efforts to strengthen or expand the existing protected area network areas that overlap the portions of the study area with particularly high biodiversity scores would protect areas with the greatest concentrations of range-restricted imperiled species. These species represent many of those with fewer opportunities for conservation interventions (*9*, *53*), for which the well-documented benefits of protected areas are likely to support their survival as the climate continues to change and conditions become more extreme.

Connectivity

In addition to protecting current biodiversity hotspots, it is also critical to expand protected area networks to include ecologically-intact landscapes that enhance connectivity between suitable habitat patches, including those that may become suitable under future climate conditions (*15*, *18*–*20*, *48*). Within the project study area, regions that remain highly connected to surrounding intact ecosystems, including those in adjacent protected areas with strong protections (such as wilderness), are likely to play an important role in climate change adaptation by allowing species movement and range shifts in response to change (Figure 6). Portions of the study area allowing highly diffuse movement (i.e., few barriers to connectivity across large areas, facilitating dispersed movement) primarily lie in the Chihuahuan Desert and Arizona/New Mexico Mountains ecoregion, which together account for over 1 million acres of the 1.4 million comprising the portion of the study area with connectivity scores above the 75% percentile (Figure 7). More concentrated corridors primarily lie in riparian zones, which harbor high levels of biodiversity and facilitate movement both internally (i.e., up and down the riparian corridor) and with adjacent upland systems (*86*).

Expanding or strengthening protected areas in these locations to maintain connected landscapes is likely to increase species movement/dispersal (*11*) and gene flow (*12*), reduce the risk of extirpation in isolated populations (*13*, *14*), and facilitate access to suitable habitat patches that can act as “stepping stones” to facilitate range shifts as climate conditions change (*1*, *15*–*17*). Although it is unlikely that protected areas can fully prevent regional extirpation of native species and changes in community composition (i.e., presence and relative abundance of native species present in a given location) due to climate change (*15*, *20*, *50*), expanding protected area networks to include lands that maintain and enhance species movement and facilitate range shifts in response to changing conditions are likely to minimize the loss of biodiversity at larger spatial scales (*2*, *15*, *18*–*20*).

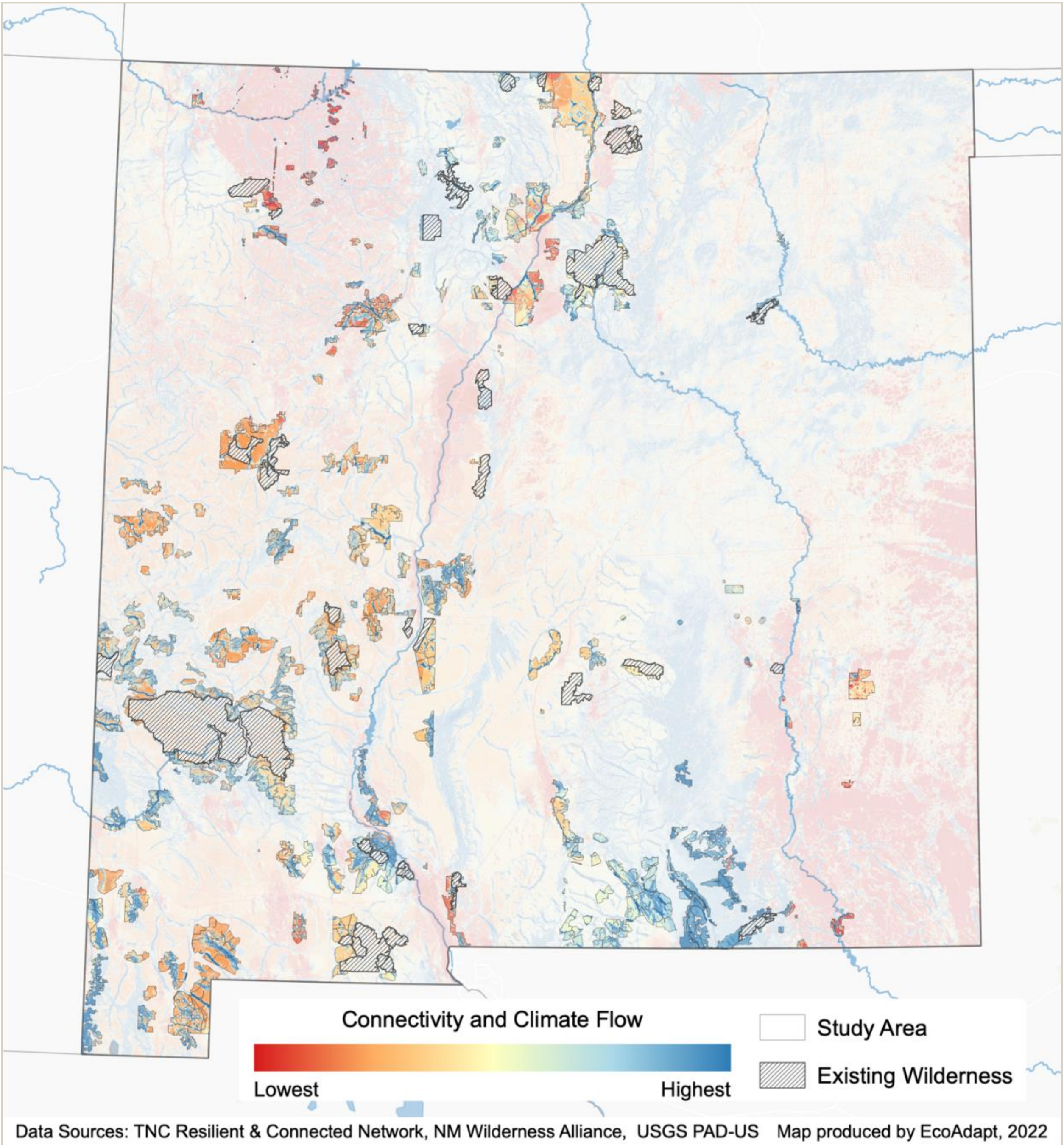

Figure 6. Connectivity and climate flow in New Mexico, highlighting connectivity values within the project study area.

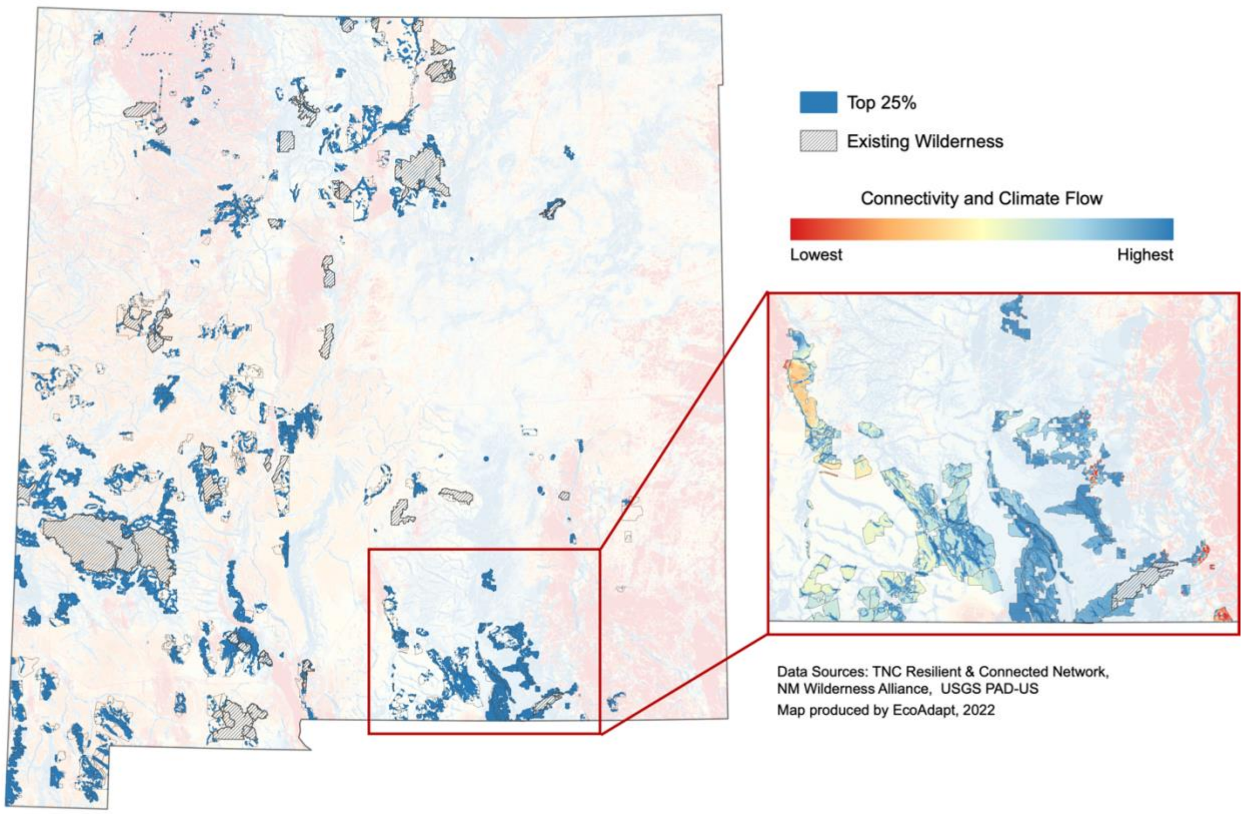

Figure 7. Twenty-five percent (25%) of the study area with the highest score for connectivity and climate flow. Inset box displays a more detailed view of the map in Figure 6 for the area where the greatest concentration of that top 25% is found, in the Chihuahuan Desert ecoregion and eastern portion of the Arizona/New Mexico Mountains ecoregion.

Resilience

Protected area networks must be able to maintain the conditions necessary to sustain biodiversity and ecosystem processes as conditions change, a characteristic often referred to as "resilience" (*21–23*). The most resilient sites typically are intact, high-quality ecosystems, particularly in high-elevation areas, riparian zones and other sites with permanent sources of surface water, and other locations where complex geophysical conditions (e.g., topography, substrate) create diverse microclimates and vegetation communities that support a wide variety of species (*24–27*). These areas may also serve as climate change refugia, which are places on the landscape that are buffered from exposure to rapid changes and climate extremes (*17*, *28*, *62*). Climate change refugia facilitate the persistence of species (particularly those with limited mobility or dispersal ability), preventing the loss of genetic diversity and buying time for adaptation over longer time scales (*17*, *62*). They also protect populations from extirpation following extreme events (e.g., severe drought or large, high-severity wildfires) (*28*, *87*), and support range shifts by providing areas where organisms from nearby regions may find suitable conditions, sometimes referred to as "stepping stones" (*1*, *16*, *26*). However, many potential climate change refugia in the most resilient areas remain unprotected, or lack the level of protection required to prevent degradation (*24–26*, *41*).

The map below (Figure 8) shows site resilience across the study area, using a dataset that considers microclimate diversity (closely linked to the presence of climate refugia) and local connectedness (tied to ecosystem integrity and species movement) to identify sites most likely to retain biodiversity and ecological function under changing climate conditions. The top 25% most resilient sites within the study area are disproportionately located in the Arizona/New Mexico Mountains ecoregion (55%), in both the southern and western portions of the state, but an additional 20% of the most resilient sites lie in the Chihuahuan Desert (Figure 9).

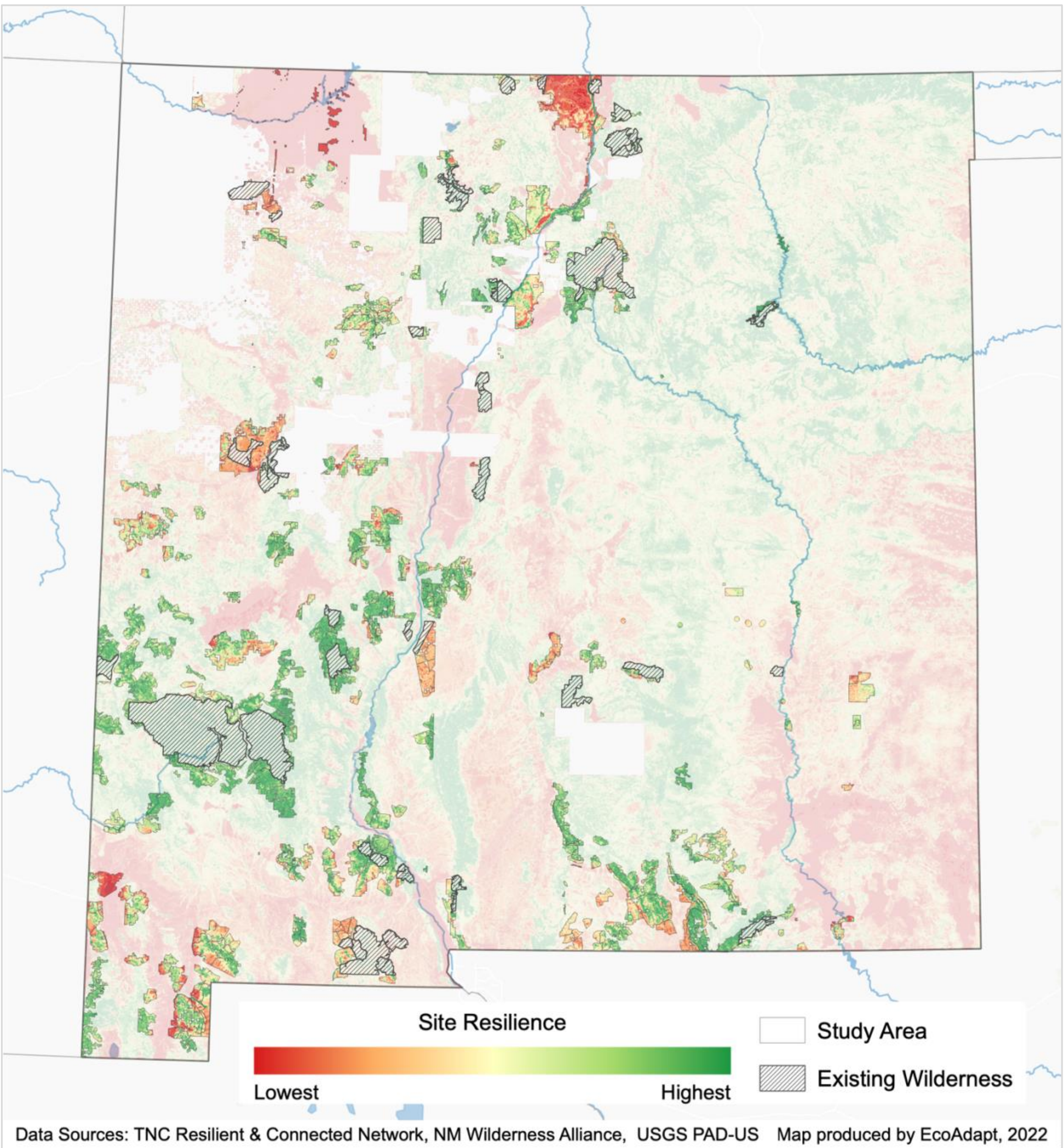

Figure 8. Site resilience in New Mexico, highlighting resilience values within the project study area.

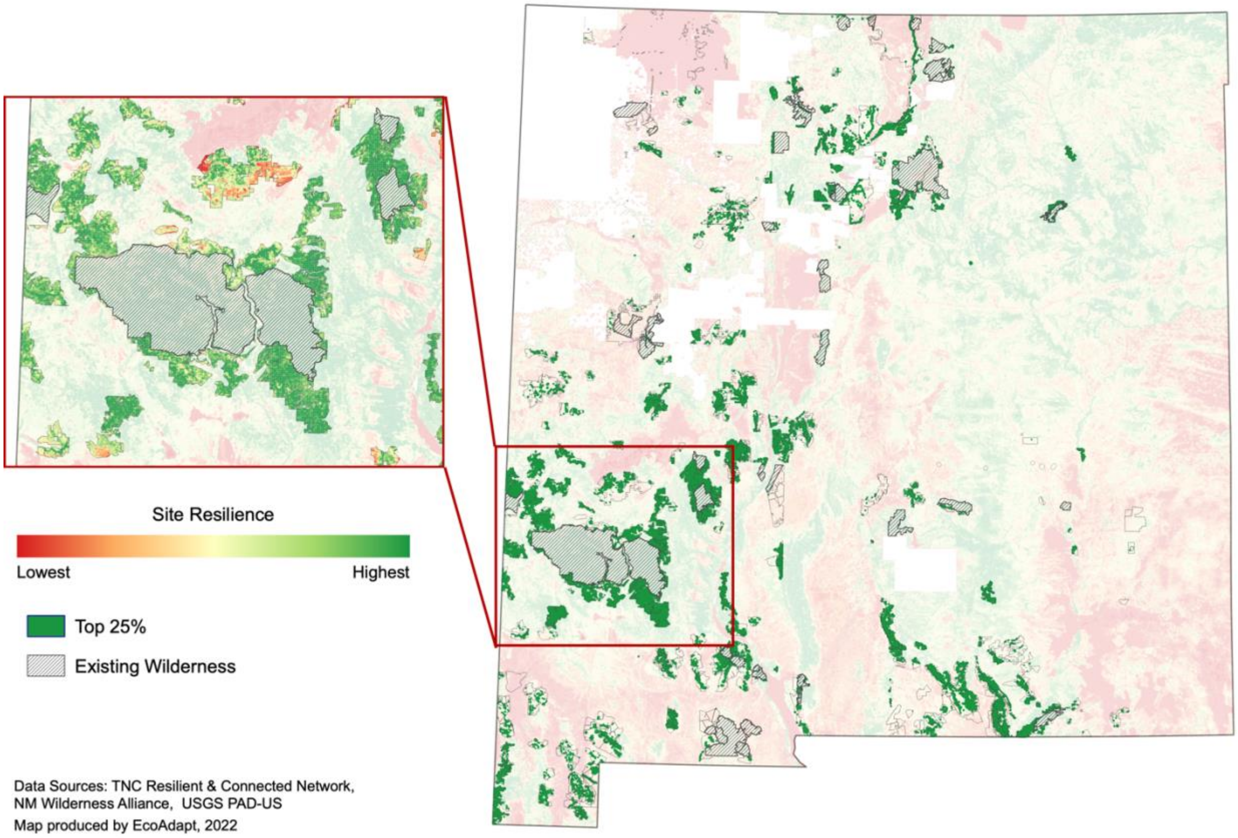

Figure 9. Twenty-five percent (25%) of the study area with the highest resilience scores. Inset box displays a more detailed view of the map in Figure 8 for the area where the greatest concentration of that top 25% is found, in the Arizona/New Mexico Mountains ecoregion.

Contribution of study area to climate change mitigation efforts

In order to meet any goal focused on climate change mitigation, it is necessary to drastically reduce greenhouse gas emissions from the production and use of fossil fuels while simultaneously increasing carbon sequestration (i.e., capture) and storage within plants and soils (*88*, *89*). Protected areas can play an important role in meeting climate mitigation targets by preventing the loss of carbon sequestration and storage following land-use conversion and human activities that result in carbon losses (*29*–*32*). Similarly, protected area designations that prevent fossil fuel development (e.g., wilderness areas) also have the potential to reduce greenhouse gas emissions by keeping oil, gas, and coal in the ground (*33*, *34*).

Carbon sequestration and storage

Maximizing carbon sequestration (i.e., the rate at which carbon is removed from the atmosphere) and carbon storage (i.e., the amount and distribution of carbon stored) within plants and soil is a critical component of climate change mitigation (*30*, *78*, *88*). Overall, intact ecosystems sequester and store more carbon than those that are disturbed, making the protection of these areas a critical step in meeting near-term carbon sequestration goals (*32*, *77*, *78*, *88*). Increased atmospheric carbon dioxide, warming temperatures, altered precipitation patterns, and climate-driven changes in disturbance regimes such as wildfire and beetle outbreaks are likely to significant impact carbon sequestration and storage capacity in dryland ecosystems such as those of the southwest U.S. (*65*, *90–93*). However, these changes are accelerated by anthropogenic disturbances and land-use change that results in damage or loss of plant cover and soil (*94*, *95*). Thus, strengthening protected area status to prevent the degradation or loss of intact ecosystems as a result of human activity is another important way to support the continued functioning of the processes that support carbon sequestration (*29*, *32*), along with restoration and management activities that minimize loss of existing carbon stocks (*32*, *96*).

Under future climate conditions, carbon stocks modeled using a high-emissions scenario (RCP 8.5) are projected to be between 210.1 and 240.6 million metric tons of carbon (MMt C) by the end of the century (2070–2099), depending on the climate model used (Table 3). The models chosen represent a range of potential futures (i.e., hot/dry, hot/wet, and warm/no change), with the GFDL model (warm/no change) resulting in the greatest amount of carbon stored on the landscape, at an average of 43.5 metric tons of carbon (Mt C) per acre (Table 4). By contrast, the IPSL model (hot/dry) would result in the lowest amount of stored carbon, at an average of 37.8 Mt C per acre. However, although carbon stocks vary among these models, the relative carbon density across the study area is expected to be similar (Figure 10), with the most significant carbon storage in the Southern Rockies ecoregion where vegetation is dominated by relatively dense montane forests. End-of-century carbon stocks using the average of these three models would be 226.2 MMt C, at an average density of 40.9 Mt C per acre (Figure 11).

Table 3. Total ecosystem carbon in million metric tons of carbon (MMt C) for the study area and state-wide, modeled for under end-of-century (2070–2099) climate conditions using three climate models (GFDL-ESM2M, CanESM2, IPSL-CM5A-MR) under a high-emissions scenario (RCP 8.5).

	Total Ecosystem Carbon (MMt C)			
Area	**GFDL** *(Warm/ No Change)*	**CanESM2** *(Hot/Wet)*	**IPSL** *(Hot/Dry)*	**Model Average**
Study Area	240.6	227.8	210.1	226.2
New Mexico (state-wide)	3,126.0	3,009.9	2,736.0	2,992.5

Table 4. Average carbon density (Mt C/acre) for the study area, broken down by ecoregion, and state-wide, modeled for end-of-century (2070–2099) climate conditions using three climate models (GFDL-ESM2M, CanESM2, IPSL-CM5A-MR) under a high-emissions scenario (RCP 8.5).

	Average Carbon Density (Mt C/acre)			
Area	**GFDL** *(Warm/ No Change)*	**CanESM2** *(Hot/Wet)*	**IPSL** *(Hot/Dry)*	**Model Average**
Arizona/New Mexico Mountains	47.4	44.1	40.3	43.9
Arizona/New Mexico Plateau	36.3	34.6	33.3	34.7
Chihuahuan Deserts	32.2	31.0	29.4	30.9
Colorado Plateaus	37.1	35.5	33.4	35.4
High Plains	27.4	27.2	25.8	26.8
Madrean Archipelago	33.6	31.8	30.9	32.1
Southern Rockies	94.5	92.0	74.6	87.2
Southwestern Tablelands	34.1	32.9	31.4	32.8
Study Area	**43.5**	**41.4**	**37.8**	**40.9**
New Mexico (state-wide)	**40.9**	**39.4**	**35.8**	**38.8**

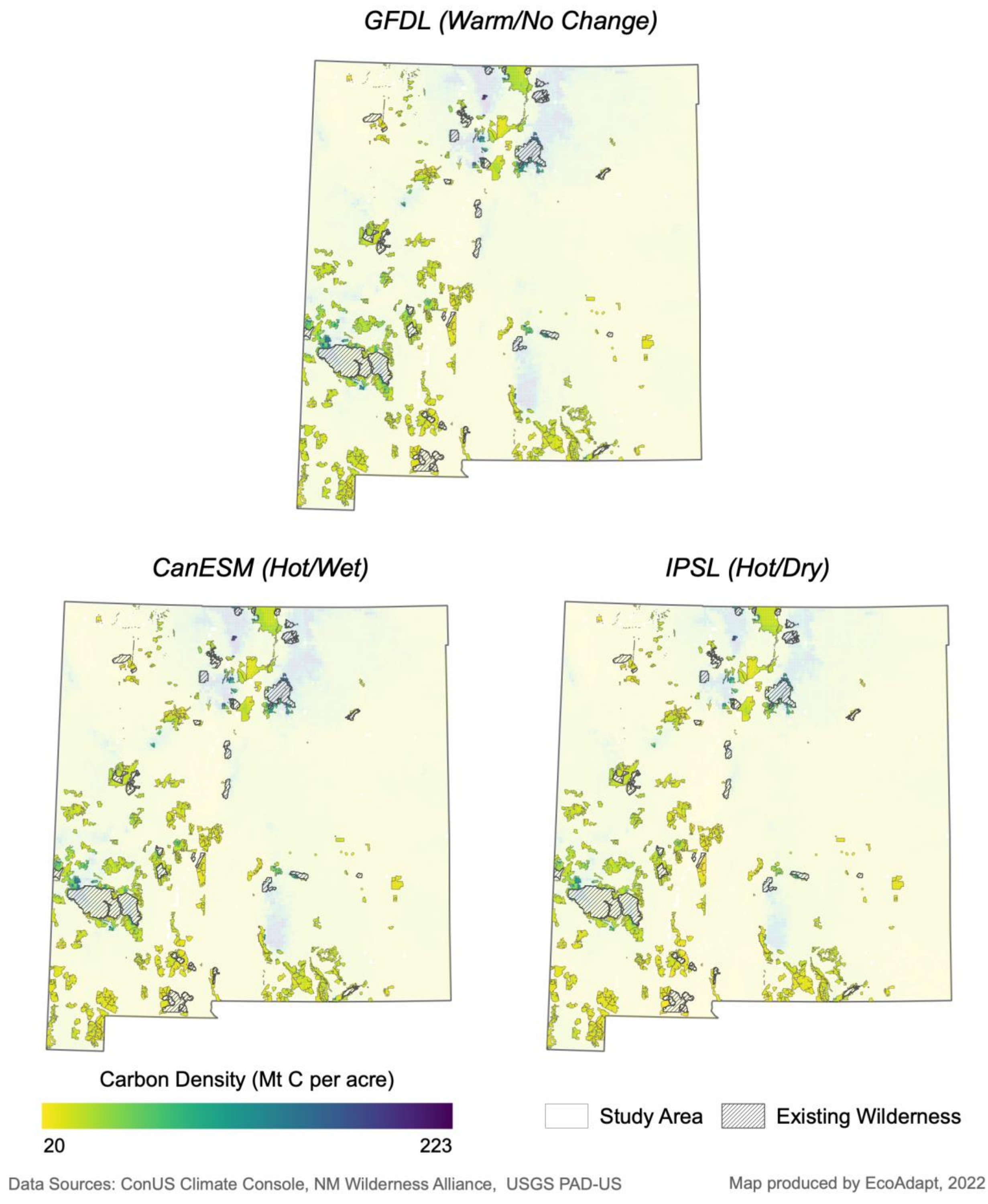

Figure 10. End-of-century (2070–2099) ecosystem carbon stocks (in Mt C/acre) for three separate climate models representing a range of potential futures, including GFDL-ESM2M (warm/no change in precipitation), CanESM2 (hot/wet), and IPSL-CM5A-LR (hot/dry) run under a high-emissions scenario (RCP 8.5).

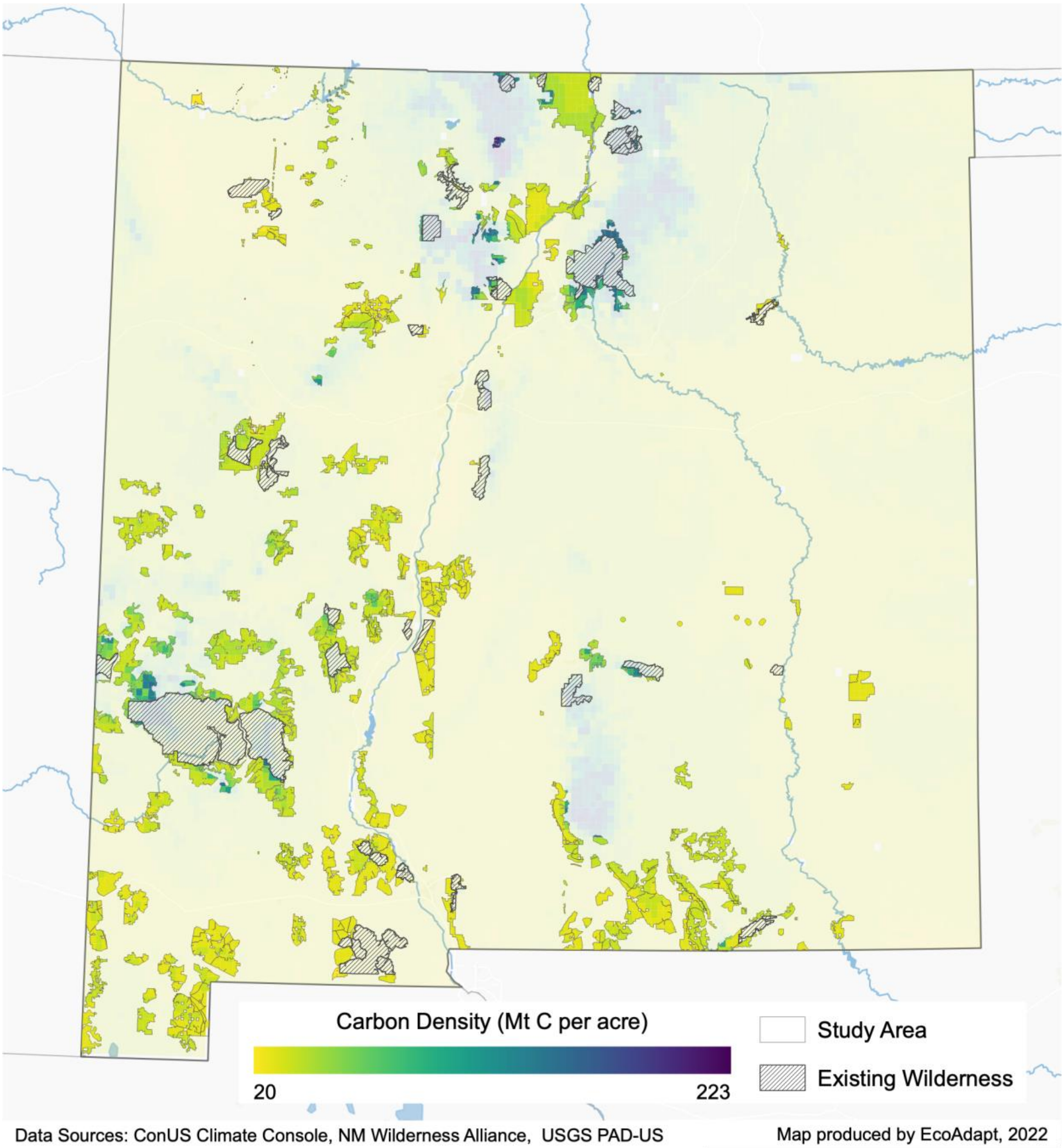

Figure 11. End-of-century (2070–2099) ecosystem carbon stocks (in Mt C/acre), using the average of three climate models (GFDL-ESM2M, CanESM2, IPSL-CM5A-LR) run under a high-emissions scenario (RCP 8.5).

Within the 5.8-million-acre study area, 38% of the carbon is found within 25% of the total acres (about 1.45 million acres; Figure 12). These areas are concentrated in more forested ecoregions where carbon density is highest, including the Southern Rockies, Arizona/New Mexico Mountains, and Arizona/New Mexico Plateau. Expanding protected area networks in order to maximize carbon sequestration and storage potential under future climate conditions would benefit from the prioritization of forested areas in the Southern Rockies such as the Canjilon

Mountain Roadless Area, which has the highest projected carbon stocks per acre (up to 49,710 Mt C per acre). Preventing degradation from human disturbances or land-use change in these carbon-dense areas is likely to play an important role in preventing loss of existing carbon stocks and ensuring continued carbon sequestration into the future, particularly if paired with climate-informed forest restoration and management (e.g., thinning, planting) designed to increase forest resilience to disturbances that result in carbon losses (*32*, *96*).

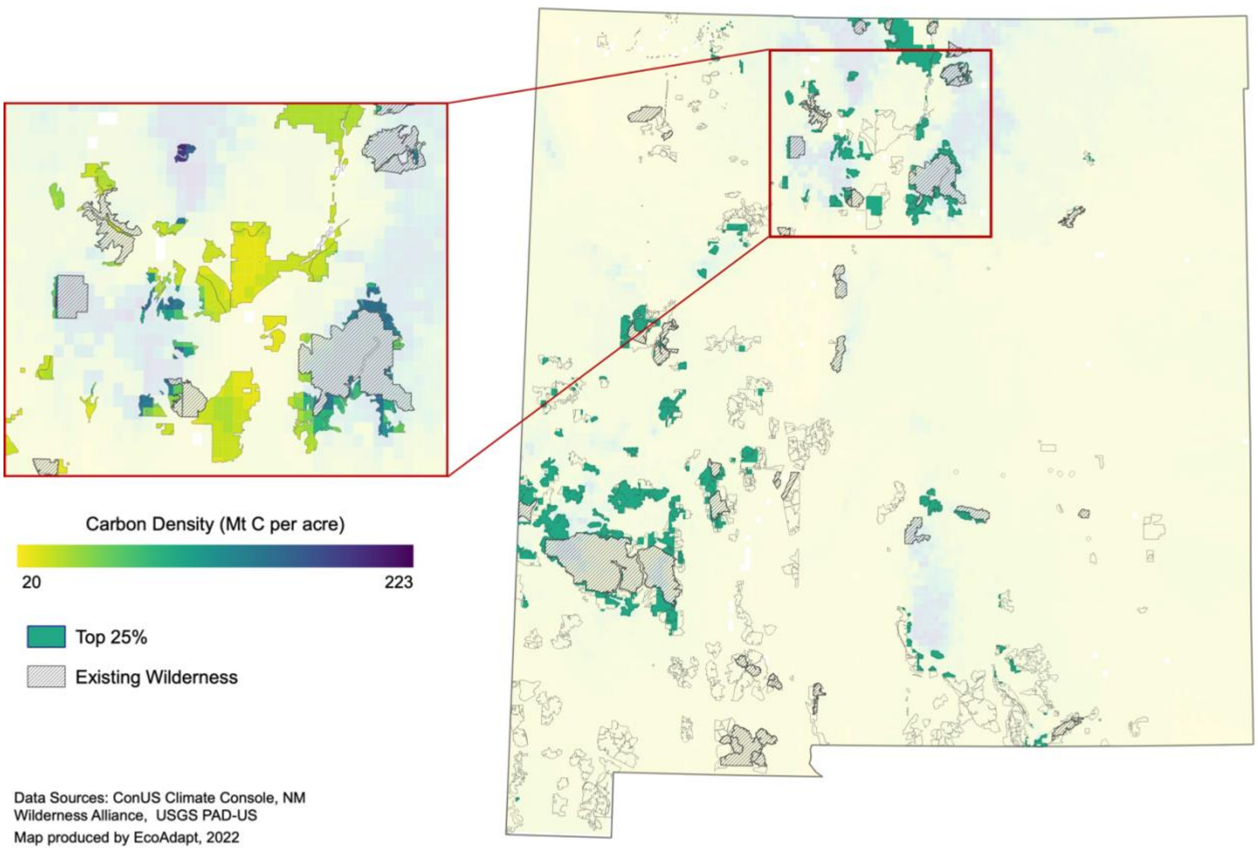

Figure 12. Twenty-five percent (25%) of the study area with the highest carbon density in metric tons carbon (Mt C) per acre. Inset box displays a more detailed view of the map in Figure 10 for the portion of the study area where carbon density is highest (up to 49,710 Mt C/acre), in the Southern Rockies ecoregion.

Greenhouse gas emissions associated with unleased fossil fuels

Nationally, a large proportion of energy production comes from public lands in the western U.S. (*97*), which are leased by federal agencies to private companies for oil, gas, and coal extraction and sale. While these leases offer a limited number of years for leaseholders to begin extraction (10 years for oil/gas or 20 years for coal), leases last indefinitely once production begins (*33*). Although federal agencies are not required to track greenhouse gas emissions associated with fossil fuel production on public lands, studies suggest that they account for over 20% of national emissions (*37*, *97*) and up to 50% of all remaining unleased U.S. fossil fuels (*33*). Multiple recent analyses (*33*, *34*) have found that unchecked production and end use consumption of remaining unleased fossil fuels in the U.S. would result in lifecycle emissions that far exceed the reductions required to avoid a 1.5°C rise in global temperature, a goal established by the United Nations and set out in the Paris Agreement (*98*). These analyses and others (*35*, *36*) suggest that keeping oil, gas, and coal in the ground has the potential to significantly contribute to climate mitigation efforts.

Part of the study area for this analysis falls within the San Juan and Permian basins, which represent the most productive areas for oil and gas extraction within the state. Although most of these basins have already been leased, we estimate that fossil fuels underlying remaining unleased portions of the study area may include 2,752 million barrels of crude oil (MMBbl), 3,075 billion cubic feet of natural gas (Bcfg), and 403 million short tons of coal (MMSt; Table 5). Together, these fossil fuel resources are associated with lifecycle greenhouse gas emissions of 2,943 million metric tons of carbon dioxide equivalent (MMt CO_2e). Of these potential emissions, oil accounts for the largest proportion (57%), followed by coal (35%) and gas (8%). To put this into context, this amount of is equivalent to about 5.3 months of greenhouse gas emissions for the entire U.S. at 2018 levels, which were 6,644 MMt CO_2e annually (*37*).

Table 5. Estimates of remaining unleased oil (MMBbl), natural gas (Bcfg), and coal (MMST) resources in the study area and associated lifecycle greenhouse gas emissions (MMt CO2e) based on 100-year global warming potential for carbon dioxide, methane, and nitrous oxide.

Fossil Fuel Type	**Resources**	**GHG Emissions *(MMt CO_2e)***
Crude oil *(MMBbl)*	2,751.5	1,680.3
Natural gas *(Bcfg)*	3,074.6	243.4
Coal *(MMSt)*	402.8	1,019.7
Total Greenhouse Gas Emissions		**2,943.4**

Within the study area, the regions where preventing additional development of unleased fossil fuels would have the greatest impact on greenhouse gas emissions is in the northwest and southeast portions of the state, which overlap the San Juan Basin and Permian Basin, respectively (Figure 13). In total, 12.8% of the 5.8 million-acre study area is estimated to have underlying fossil fuel resources that are currently unleased (738,872 acres). Forty percent (40%) of that area (just under 300,000 acres) is in the Arizona/New Mexico Plateau ecoregion, with an additional 24% and 20% in the Arizona/New Mexico Mountains and Chihuahuan Desert ecoregions, respectively.

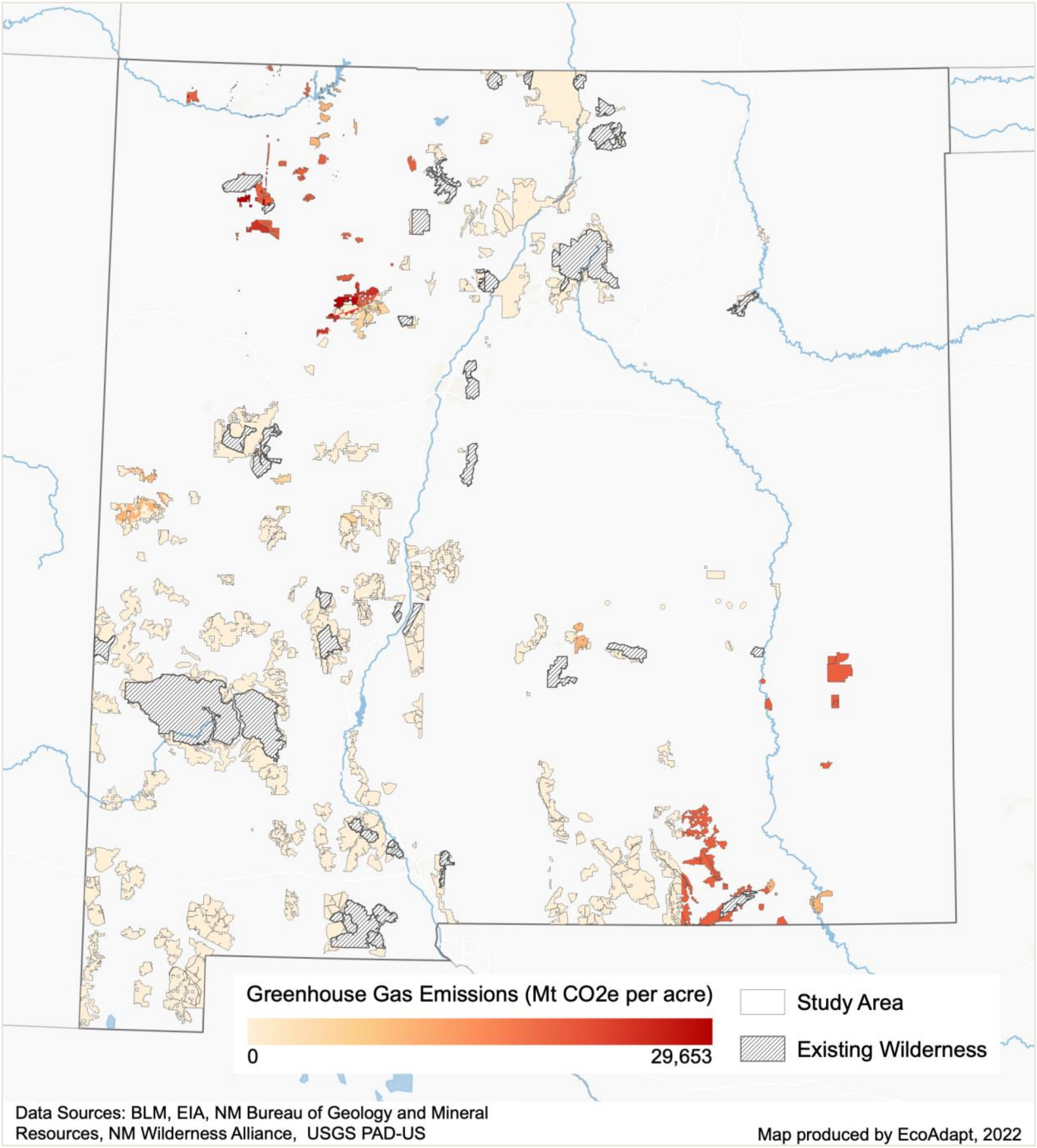

Figure 13. Greenhouse gas emissions associated with unleased fossil fuels underlying the New Mexico study area.

While it would not be possible to extract 100% of all fossil fuels on every acre of the study area (due to multiple use conflicts, economic constraints, and other factors), the results of this analysis illustrate the potential value of including unleased fossil fuels when considering the potential climate mitigation value of protected areas on New Mexico public lands. Protecting additional areas as wilderness, in particular, would ensure that new lease sales and resource extraction would be permanently prohibited, preventing the release of greenhouse gasses associated with the production and combustion of any fossil fuels underlying those lands.

Priority areas across multiple adaptation and mitigation indicators

Across the five adaptation and mitigation indicators examined in this project, several portions of the study area emerge as relatively consistent priorities for protection in the context of climate change (Figures 14 and 15). Specifically, regions that represent priorities based on their identification in the top 25% of multiple indicators are found around several existing wilderness areas, including Gila, Aldo Leopold, Apache Kid, Carlsbad Caverns, and Pecos, along with a few other portions of the study area in the Southern Rockies (Figure 16). Protected areas that were mapped as priorities for all five indicators include portions of the Guadalupe Escarpment Wilderness Study Area and the Tucson Mountains, Madre Mountain, and Carrizo Mountain Roadless Areas, among others. Prioritizing efforts to expand and/or strengthen the protected area network in these locations has the potential to deliver the greatest climate change benefits within the study area, including both support of ecosystem adaptation to climate change as well as mitigation efforts.

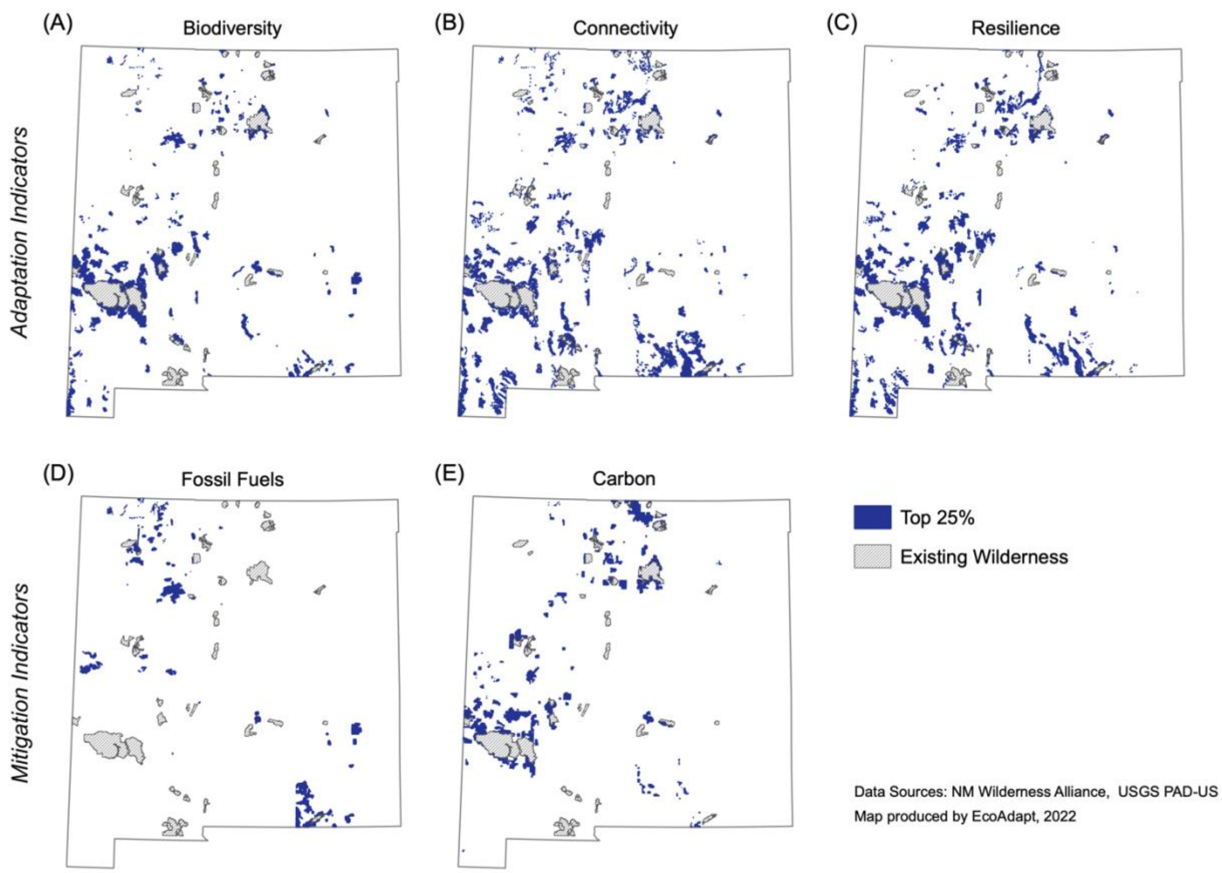

Figure 14. Twenty-five percent (25%) of the study area with the highest scores for each of five adaptation and mitigation indicators, representing priority areas for protection.

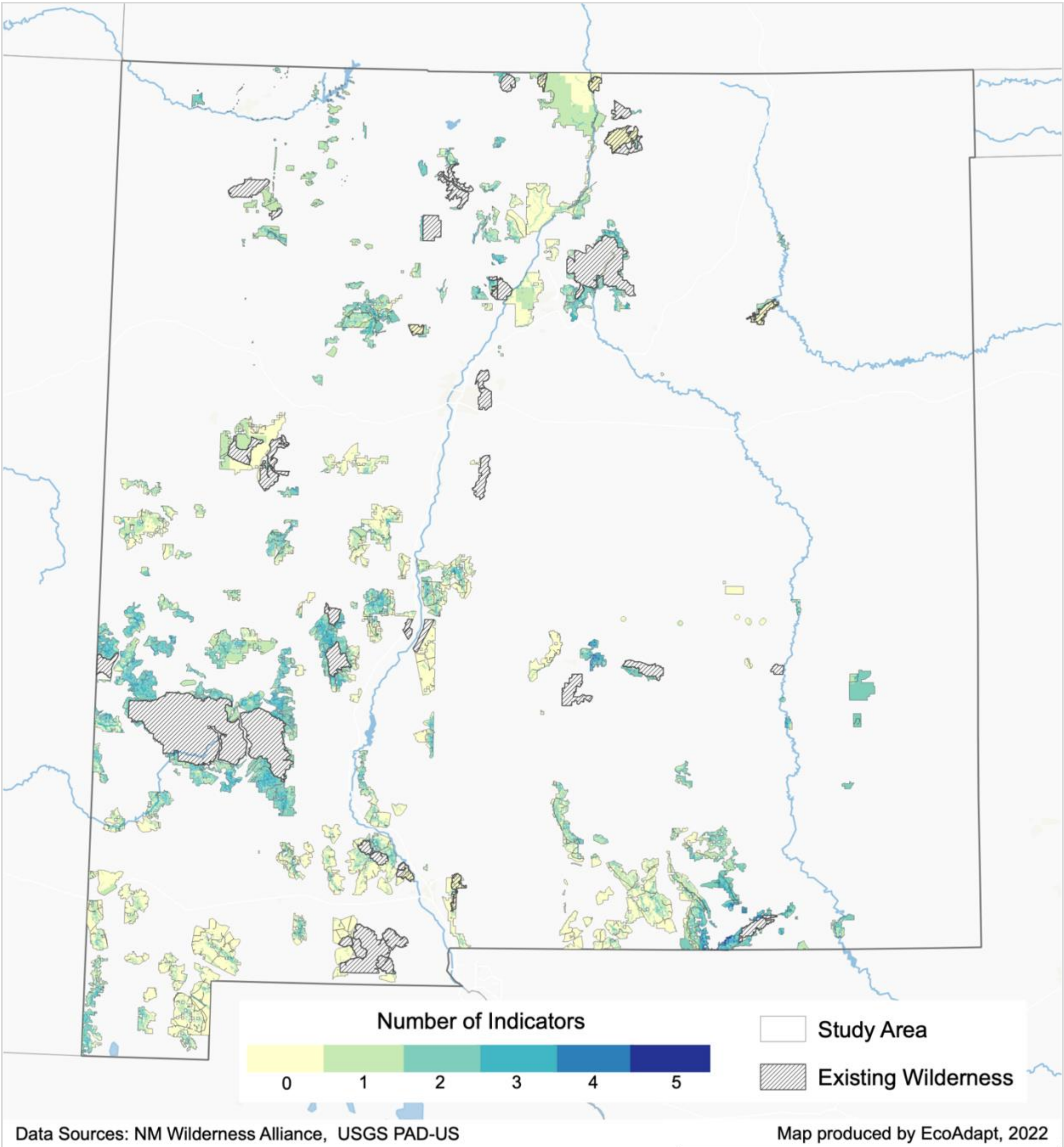

Figure 15. Priority areas based on number of adaptation and mitigation indicators for which portions of the study area have scores in the top 25%.

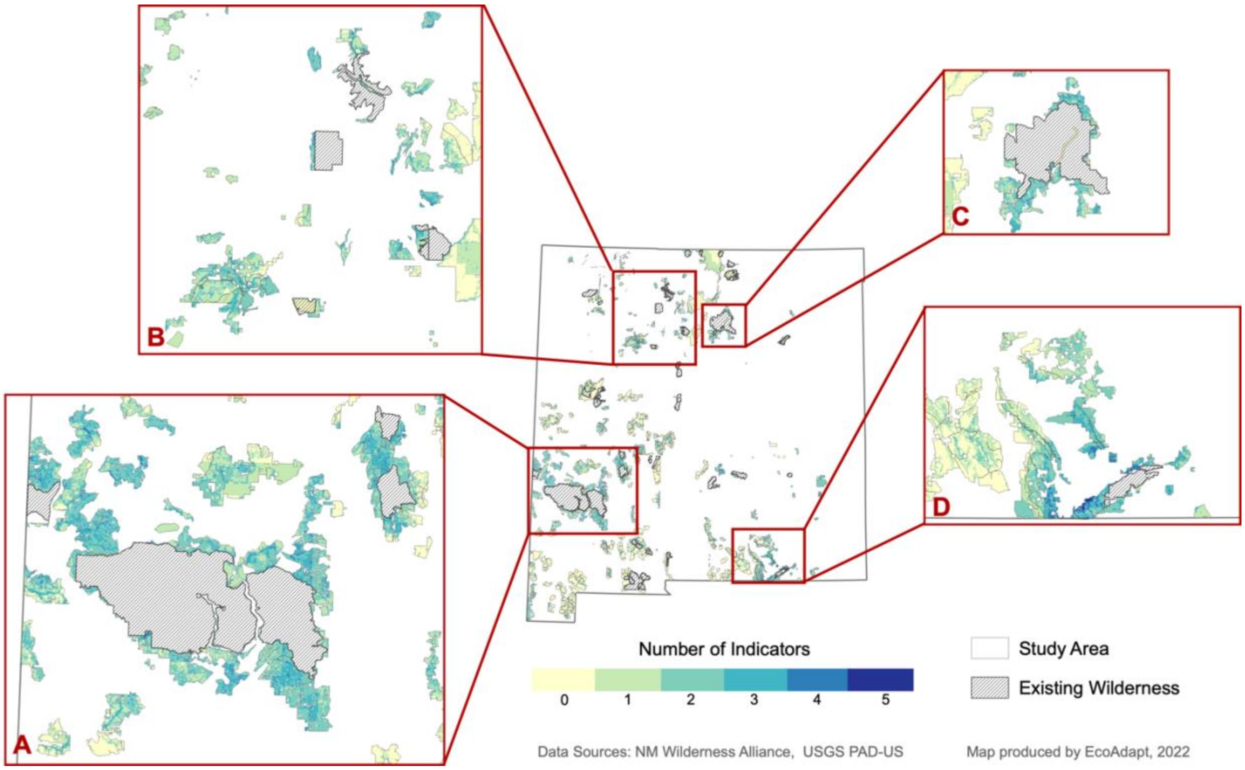

Figure 16. Detailed views of the map in Figure 15 for portions of the study area where scores for the majority of adaptation and mitigation indicators were in the top 25%. **(A)** Portions of the study area in the vicinity of the Gila, Aldo Leopold, Blue Range, Apache Kid, and Withington wilderness areas. **(B)** Portions of the study area within the Southern Rockies ecoregion, near the San Pedro Parks, Chama River Canyon, Bandelier, and Dome wilderness areas. **(C)** Portions of the study area around the Pecos Wilderness. **(D)** Portions of the study area in the vicinity of the Carlsbad Caverns Wilderness.

Conclusions

The results of this analysis provide an initial view of federally-owned public lands in New Mexico that should be considered priorities for expanding and strengthening the existed protected area network to meet 30x30 goals at both the national and state levels. While the indicators selected for this study do not provide a comprehensive evaluation of adaptation and mitigation benefits, they do represent several important climate change considerations and can act as a coarse filter for evaluating the climate benefits of protecting New Mexico public lands.

Based on the findings of this study, the following actions are recommended:

- ***Add or strengthen protected status in areas that provide the greatest benefit across multiple indicators*** (e.g., parcels that harbor range-restricted imperiled species, are resilient and have high levels of connectivity, and hold significant carbon stocks). Additional considerations might include areas with particularly high ecological integrity (such as Wilderness Study Areas or those identified as having wilderness characteristics) and those that are adjacent to or would enhance connectivity among existing protected areas.

- ***Ensure that both new and existing protected areas are protected from disturbances or human uses that would degrade the structure and function of the ecosystem***. This is particularly critical for areas such as headwaters, wetlands, and riparian zones, which harbor high levels of biodiversity and are likely to serve as climate refugia and critical movement corridors as climate change makes the surrounding areas less suitable for sensitive species. These areas will also serve an increasingly important role maintaining water supply and quality within the watershed as climate change increases water stress, both for natural and human communities.
- ***Practice climate-informed management and restoration to maximize the potential for ecosystem adaptation and mitigation***. As climate change increases environmental stress and the frequency and severity of disturbances such as wildfire and insect outbreaks, it will be critical to ensure that management practices and restoration projects in protected areas are designed to maintain biodiversity and ecosystem functioning under both present and future climate conditions. In some instances, this may result in shifts within the system (i.e., in terms of species composition or vegetation cover) that better align with future conditions. In others, management actions such as thinning to reduce forest density in areas impacted by historical fire suppression may increase the health and resilience of current ecosystems that have been degraded by human land uses or management.
- ***Ensure that tribal values and priorities are explicitly incorporated into conservation and management plans***. Protected area designation should preserve treaty rights on federal lands, such as hunting, timber harvest, and use of culturally-important sites and resources, and should seek to integrate cultural values and tribal priorities such as protection of sacred sites or restoration of culturally-important resources (*99*). Increasing opportunities for tribal co-management of federal lands and incorporating traditional ecological knowledge and perspectives into protected area management is an important step towards respecting the relationship of area tribes with their homelands, while also increasing ecosystem health and resilience.
- ***Collaborate with state, local, and tribal governments to meet 30x30 goals***. Although federally-owned lands make up a significant portion of New Mexico and other western states, the protection of federal public lands is unlikely to be adequate to meet 30x30 goals within the specified timeframe (*56*). In order to meet these goals, protected area networks must be strategically expanded to include state, local, and tribal lands that meet the criteria set for inclusion.

Appendix A

Overview of New Mexico study area

New Mexico landscapes are characterized by large gradients in precipitation, elevation and temperature as well as varied geophysical conditions (e.g., substrate, topography) that have given rise to significant biological diversity, including many endemic and rare plants and animals (*83*, *84*, *100*). New Mexico shares several major ecoregions with neighboring states (Figure 2), including:

- The southern edge of the **Colorado Plateau**, which is located in the northwestern corner of the state, is characterized by rugged topography and dominated by sparse woodlands, shrubs, and drought-tolerant grasses.
- The **Southern Rockies**, which represent the southern extent of the Rocky Mountain range and are primarily dominated by coniferous forests. Some alpine habitat also occurs on the highest peaks.
- The **Arizona/New Mexico Plateau**, which occupies much of the western portion of the state, is dominated by a combination of shrublands, grasslands, and pinyon-juniper woodlands.
- The **Arizona/New Mexico Mountains**, which are warmer and drier than their northern counterparts in the Southern Rockies. Major vegetation types include shrublands at lower elevations, pinyon-juniper and oak woodlands at lower and middle elevations, and ponderosa pine forests at higher elevations.
- The **Chihuahuan Desert**, which occupies large areas in the southern portion of the state and also extends south into Mexico, is dominated by grasslands and shrublands with higher-elevation islands of oak (*Quercus* spp.), juniper (*Juniperus* spp.), and pinyon pines (*Pinus* spp.).
- The **Madrean Archipelago** in the extreme southwestern corner of the state extends westward into Arizona and southward into Mexico. This ecoregion is characterized by "sky islands", where high-elevation pine- and oak-dominated systems are interspersed with lower-elevation grasslands and shrublands.
- The **Southwestern Tablelands**, which are dominated by sub-humid grasslands and semi-arid rangelands, with juniper-scrub oak savannah along escarpment bluffs.
- The **High Plains** in the far eastern portion of the state, dominated by native grasses where they are not converted to croplands, and containing thousands of playa lakes important to waterfowl migration (*100*).

Current uses of public lands in New Mexico are wide-ranging, and include many uses that can be compatible with conservation such as wildlife viewing, hiking, biking, fishing, camping, rafting, and horseback riding, as well as those that can have negative impacts on ecosystem integrity such as ORV use, livestock grazing, oil and gas drilling, and mining, among others. Like much of the U.S., many of New Mexico's public lands are threatened by the expansion of invasive plants that compete with and displace native species, change soil chemistry and nutrient cycling, and alter fire regimes (*101–103*). Land use changes associated with grazing and livestock movement, in particular, has facilitated the spread of many species such as mesquite (*Prosopis sp.*), and have been a driving force for shifts in community composition (*104*).

A significant challenge for protecting natural areas across much of the state is water stress. As a largely arid- and semi-arid state, New Mexico's ecosystems are adapted to relatively dry conditions, and also to temporal and geographic variability in precipitation. However, anthropogenic use of water and manipulation of water systems constitutes an additional significant stressor for the state, where nearly 500 dams have altered the natural flows in the majority of river reaches (*105*). Some parts of the state have also experienced significant aquifer declines, as groundwater makes up the majority of New Mexico's public water supply (*106*). Existing water appropriation systems further exacerbate water stress. For instance, the Rio Grande Compact of 1938, which dictates how much water must be sent from downstream to Texas, is based on hydrological conditions from 1929 and fails to take into account population growth and changing climate factors that impact water availability (*107*). Efforts to provide additional protection to riparian systems and surface water features could be undermined if problematic legal/management structures as well as issues of overallocation and overuse of surface and groundwater supplies that support natural systems are not adequately addressed.

Projected climate impacts on New Mexico public lands and associated ecosystems

Across the state, public lands are projected to experience rapid shifts in climate conditions and disturbance regimes over the coming century (see Table A1).

Table A1. Projected future changes in the primary climate stressors likely to impact New Mexico public lands. Arrows represent the trend direction (e.g., increase, decrease, or shift towards earlier timing).

Climate Stressor	Trend Direction	Projected Future Changes
Air Temperature	▲	• 7.7–15.3°F (4.3–8.5°C) projected increase in maximum annual temperature and 6.3–12.6°F (3.5–7.0°C) increase in minimum annual temperature in New Mexico by 2100 (*63*)
Precipitation	▲ ▼	• –24% to +42% change in mean annual precipitation in New Mexico by 2100 (high uncertainty in the direction/amount of change) (*63*) • Likely seasonal shift towards wetter winters and drier springs and summers, along with increases in interannual precipitation variability and the frequency of extreme precipitation events (*108*, *109*)
Snowpack & Snowmelt	▼ ◀	• Decreased proportion of precipitation falling as snow and significant reductions in snowpack, and earlier snowmelt (*110–114*)

Climate Stressor	Trend Direction	Projected Future Changes
Streamflow	▼ ◀	• Likely reductions in annual streamflow due to increased evapotranspiration, even if precipitation increases (*114*, *115*) • Likely shift towards earlier spring peak flows and reduced volume of peak flows due to changes in snowpack and snowmelt (*111*)
Drought	▲	• Increased risk of prolonged and/or severe drought, with a >70% chance of multi-decadal drought by 2100 (*116–118*)
Wildfire	▲	• Increased fire frequency (*119*, *120*) and annual area burned (*121*) over the coming century, including a significant increase the likelihood of very large fires (*122*)

Ecological implications of climate change

Climatic changes within the region may result in:

- Increased evapotranspiration rates, driving shifts toward higher aridity even in the absence of precipitation declines (*114*, *116*, *123*, *124*).
- Reduced plant productivity and increased mortality due to greater water stress (*93*, *125–128*).
- Changes in plant functional group dynamics, leading to shifts in community composition (e.g., increased relative dominance of shrubs and invasive annual grasses over native perennial grasses) (*129*, *130*).
- Reductions in surface water availability and quality (*114*, *131*), with significant impacts for riparian vegetation (*12*, *132*) and aquatic communities (*133*).
- Increased risk of ecosystem type conversion (e.g., forests to shrubland or shrubland to non-native grassland) due to frequent and/or severe wildfires, particularly in drier areas and during periods of drought (*134–137*).
- Reduced habitat suitability/loss of core habitat and possible species range shifts towards northern latitudes and/or higher elevations (*51*, *138*), with likely loss of high-elevation montane habitat islands (*26*, *139*).
- Range contractions and/or local extirpation, particularly for range-restricted species and those that are unable to track suitable habitat (i.e., due to dispersal limitations or low landscape permeability) (*60*, *81*, *140*, *141*).
- Increased habitat fragmentation as a result of extreme events that reduce patch size, increase gaps, and/or block colonization (*142*).
- Loss of genetic diversity and species richness, particularly where species are already coping with habitat fragmentation and loss (*12*, *143*).
- Changes in carbon sequestration and storage due to reduced overall plant productivity (*93*), shifts in plant community composition (*91*), and altered soil community composition and activity (*92*, *93*).

Interactions between existing stressors and climate change

The impacts of climate change can interact with existing threats to species and ecosystems, including disturbances such as livestock grazing, ORV use, mechanical vegetation treatments, oil and gas development, and road construction, among others. On New Mexico public lands, examples of significant interactions that may occur include:

- Altered hydrology, reduced freshwater availability, and reduced water quality where human use and disturbances of public lands and adjacent areas degrade intact watersheds (*144*–*147*) or result in large water withdrawals and discharge of contaminated water. Warmer, drier climate conditions and more frequent extreme precipitation events are likely to exacerbate the impacts of existing water stress on native plants and animals while also increasing pressure to develop remaining water resources for human use (*114*, *148*).
- Shifts away from historical hydrologic regimes as a result of climate change results in existing water allocation systems being based on conditions that no longer exist, resulting in increasingly unsustainable practices that exacerbate current inequities (*107*)
- Increased spread and establishment of invasive plants that displace native plant species, alter ecosystem processes, and degrade critical wildlife habitat (*101*, *149*, *150*). The expansion of cheatgrass (*Bromus tectorum*), in particular, has increased wildfire frequency and annual area burned by enhancing fuel availability and continuity (*103*, *151*). Frequent fires, in turn, increase the cover of invasive grasses, creating a positive feedback loop that perpetuates altered fire regimes (*102*, *152*). Warmer temperatures and increased drought are projected to enhance wildfire risk and contribute to the spread of invasive grasses over the coming century, further strengthening invasive grass-fire feedback loops (*153*, *154*).
- Anthropogenic disturbances that reduce carbon sequestration and storage due to vegetation loss, increased erosion, and changes in soil properties. The removal of woody vegetation is generally associated with a short-term net loss of stored carbon, due to both the removal of above-ground plant biomass (*91*, *155*, *156*) as well as changes in carbon cycling that reduce soil organic carbon (*157*, *158*). However, climate-informed forest restoration focused on stabilizing long-term carbon storage may include tree removal through thinning practices designed to increase tree productivity and vigor while also reducing the vulnerability of carbon losses to wildfire (*32*, *96*).

Appendix B

Detailed methodology for fossil fuel analysis

Estimates of crude oil and natural gas and associated greenhouse gases was adapted from the methodology used in a recent report by The Wilderness Society (*34*), while coal estimates were adapted from Mulvaney et al. (*33*). All spatial data was processed and analyzed using QGIS 3.16 (*159*). Because the New Mexico study area lands are not contiguous or uniformly distributed, we were limited by the availability of parcel-level spatial data that would allow us to determine where the study area overlapped unleased fossil fuel resources.

This analysis attempts to estimate the amount of fossil fuel resources that underlie the study area in order to determine the amount of greenhouse gas emissions that would be associated with the extraction and combustion of those fuels. Because it is impossible to account for all of the complex, interacting factors that influence whether fossil fuel resources are developed, we do not attempt to account for potential competition among different fuel types (e.g., co-occurring fossil fuel deposits). However, we have utilized location-specific parameters and constraints related to technical/economic feasibility whenever possible in order to increase the accuracy of these estimates and avoid unnecessary overestimation of recoverable resources. Additional sources of uncertainty associated with greenhouse gas emissions from fossil fuels includes method of extraction (efficiency), methane leakage rates, method of well/mine abandonment, transport distance, and end-use product, among others (*33*, *37*).

Because existing leases must be honored, we excluded these from the acreage used to estimate fossil fuel resources. We also made the simple assumption that all unleased resources could be leased at some point in the future, as "no leasing stipulations" and other limitations based on current policies and land uses could be altered or eliminated in the future. Spatial data representing current leases in New Mexico was obtained from the New Mexico Bureau of Land Management for oil and gas (*160*) and from the Mining and Minerals Division of the New Mexico Energy, Minerals, and Natural Resources Department (NM EMNRD) for coal (*161*).

Crude oil and natural gas

We used basin and/or play-specific assumptions of average well densities (*72*, *162*) and estimated ultimate recovery (EUR) (*73*) for representative wells in New Mexico to estimate production separately for oil and gas wells. Spatial data and maps showing sedimentary basins (*69*) and tight oil and shale gas plays (*70*, *71*) were used to determine the geographic distribution of production assumptions applied to the New Mexico study area, which were concentrated in the San Juan and Permian Basins.

Lifecycle greenhouse gas emissions were calculated using standard emission factors from the Bureau of Land Management (*73*).

Coal

In order to calculate coal resources underlying the study area lands, we utilized estimates of remaining recoverable coal resources in New Mexico based on a 2017 report published by the New Mexico Bureau of Geology and Mineral Resources and the New Mexico Geological Society (*75*), which represents the most recent estimates available for the state. We calculated the proportion of each coalfield that overlapped with the study area, and then assigned a corresponding proportion of the estimated recoverable coal resources for that coalfield. Because we lacked spatial data displaying distribution within the coalfields (e.g., location of coal seams, etc.), our estimates are made using the assumption that coal resources are evenly distributed across each field.

As for crude oil and natural gas, we utilized standard greenhouse gas emission factors from the BLM (*73*), which for coal were provided as a state-specific average including direct, indirect, and end-use emissions.

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