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Introduction

The objective of this assessment was to identify and describe ecological values and potential threats within the proposed 584,257-acre Otero Mesa Area of Critical Environmental Concern (ACEC) that relate to ACEC relevance and importance criteria. Specifically, we quantified these values and threats relative to other areas in the West and within Bureau of Land Management lands to evaluate the regional (i.e., more than local) significance of the proposed Otero Mesa ACEC. To meet formal ACEC relevance criteria, a given area must have at least one of the following: 1) significant historic, cultural, or scenic value; 2) a fish or wildlife resource or other natural system or process; or 3) a natural hazard. Our ecological assessment focuses on the second of those items; the first and third are beyond the scope of this work but may well strengthen the basis for nomination. To meet ACEC importance criteria, the area must have one or more qualities of more than local significance that have "*special worth, consequence, meaning, distinctiveness, or cause for concern*" or have "*qualities or circumstances that make it fragile, sensitive, rare, irreplaceable, exemplary, unique, endangered, threatened, or vulnerable to adverse change*," among other criteria (Section 0.11.B.1-2, BLM Manual 1613, BLM 1988).

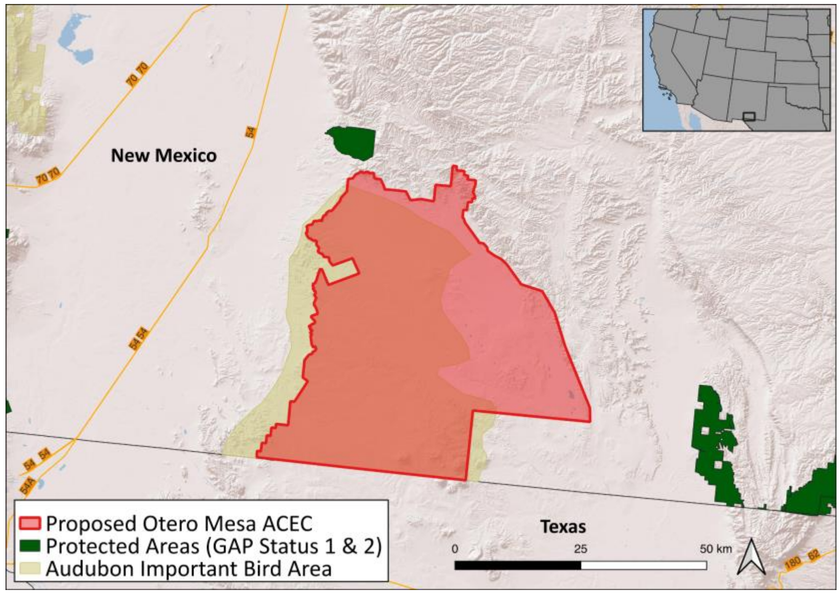
The proposed ACEC is situated in south-central New Mexico within Otero Mesa, which contains one of the largest remaining Chihuahuan desert black grama grasslands in the United States (Dunlap et al. 2009). Otero Mesa exemplifies North America's Chihuahuan desert, a desert known for the greatest diversity of cactus species in North America (McNamee 2008). The Mesa supports many rare plants such as Guadalupe mescalbean (*Sophora gypsophila var. guadalupensis*), Guadalupe needlegrass (*Stipa curvifolia*), the gray sibara (*Sibara grisea*), the cliff nama (*Nama xylopodum*) and the five-flower rockdaisy (*Perityle quinqueflora*; NatureServe 2023[1]). Otero Mesa is also home to many species of native wildlife, including pronghorn antelope (*Antilocapra americana*), black-tailed prairie dog (*Cynomys ludovicianus ludovicianus*), and over 200 species of birds (McNamee 2008).

As described below, our analysis found the proposed Otero Mesa ACEC meets multiple relevance and importance criteria. Moreover, the proposed ACEC almost entirely coincides with the Otero Mesa Important Bird Area (IBA), which provides important breeding, foraging, nesting, wintering, or migratory stop-over habitat for important avian grassland species such Swainson's hawk (*Buteo swainsoni*), ferruginous hawk (*Buteo regalis*), Northern aplomado falcon (*Falco femoralis*), mountain plover (*Charadrius montanus*), burrowing owl (*Athene cunicularia*), loggerhead shrike (*Lanius ludovicianus*), Sprague's pipit (*Anthus spragueii*), long-billed curlew (*Numenius americanus*) and upland sandpiper (*Bartramia longicauda*) (National Audubon Society 2013). Some of these species, such as the endangered aplomado falcon, reach the northern limits of their range on Otero Mesa (McNamee 2008).

These ecological values of the proposed Otero Mesa ACEC have the potential to be adversely affected by future mineral and energy development, which are not prohibited under current management (BLM 2013).

[1] https://explorer.natureserve.org/. Accessed April 2023

Methods



Map 1. Proposed Otero Mesa ACEC.

For this assessment, we mapped and summarized 23 unique indicators of ACEC relevance and importance criteria (Table 1, Appendix 1) to highlight the ecological values, their significance, and causes for concern within the Otero Mesa ACEC. These included 15 indicators that characterize the ***relevance and importance of ecological values***, namely amphibian species richness, bird species richness, mammal species richness, reptile species richness, imperiled species richness, ecological connectivity, ecological intactness, ecological system diversity, ecological system rarity, climate accessibility, climate stability, geophysical diversity, geophysical rarity, water availability, and night sky darkness (see Fig. 2 and Map 2) and eight indicators related to ***threats and vulnerabilities to adverse change,*** including oil and gas resource potential, mineral resource potential, geothermal resource potential, solar resource potential, wind resource potential, future water withdrawals, erosion potential, and aquifer vulnerability (see Fig. 2 and Map 3). Data for each of these indicators were derived at a 270-m pixel resolution and were mapped across all 11 western states[2]. Because these indicators may be used independently to substantiate an ACEC nomination, any inherent correlation between indicators is immaterial.

Table 1. Indicators used to assess ACEC characteristics within the proposed Otero Mesa ACEC. See Appendix 1 for details on the source data and/or derivation of these datasets.

Indicator	Data Source	ACEC Relevance/Importance Criteria
Values		
Climate Accessibility	Hamann et al. 2015	Relevance: natural process – high climate accessibility enables species to track suitable climatic conditions; Importance: condition essential for maintaining species diversity while enduring climate change
Climate Stability	Belote et al. 2018	Relevance: natural process – high climate stability indicates potential climatic refugia; Importance: condition essential for protecting species vulnerable to climate change and facilitating adaptation in-place

[2] With the exception of erosion potential and aquifer vulnerability, which were only assessed relative to lands in New Mexico.

Ecological Connectivity	Dickson et al. 2017	Relevance and importance: fish and wildlife resource that enables natural processes including dispersal, migration, gene flow, and range shifts and is particularly critical for imperiled species or those vulnerable to adverse change
Ecological Intactness	CSP 2019	Relevance: fish and wildlife resource that protects habitat quality; Importance: may mitigate potential threats and vulnerabilities to adverse change
Ecological System Diversity	Ecological System Type, USGS 2011	Relevance and importance: provides diverse habitat underpinning plant and wildlife diversity and promotes natural processes including acclimation, adaptation, and speciation
Ecological System Rarity	Ecological System Type, USGS 2011	Relevance and importance: natural system that is rare, unique, and/or irreplaceable and has more than local significance
Imperiled Species Richness	NatureServe 2020	Relevance and importance: natural system provides habitat for rare, sensitive, and/or irreplaceable species such as Guadalupe mescalbean, Guadalupe needlegrass, cliff nama, and five-flower rockdaisy.
Vertebrate Diversity ● Amphibian species richness ● Bird species richness ● Mammal species richness ● Reptile species richness	USGS 2019	Relevance and importance: natural system provides habitat for vertebrate species diversity across a range of taxa, including many important, rare and imperiled species such as Pronghorn, ferruginous hawk, Northern aplomado falcon, peregrine falcon, mountain plover, Southwestern willow flycatcher, loggerhead shrike, Sprague's pipit, etc.
Geophysical Diversity	Theobald et al. 2015	Relevance: supports natural process of speciation
Geophysical Rarity	Theobald et al. 2015	Relevance and importance: natural systems that are rare, unique, and/or irreplaceable and have more than local significance
Water Availability	USGS 2008b	Relevance and importance: water availability affords conditions essential for maintaining fish and wildlife habitat and therefore species diversity, especially under increasing drought risk to which habitat and species may be vulnerable
Night Sky Darkness	NOAA 2012	Relevance: significant scenic and ecological value
Threats		
Future Water Withdrawals	Brown et al. 2013; USGS 2008a	Importance: may threaten or otherwise render vulnerable to adverse change important habitat
Mineral Resource Potential	USGS 2005	Importance: may threaten or otherwise render vulnerable to adverse change important habitat
Oil & Gas Resource Potential	Copeland et al. 2009; USDOI et al. 2008	Importance: may threaten or otherwise render vulnerable to adverse change important habitat
Geothermal Resource Potential	Geothermal favorability, USGS 2008b; Hanser 2004; GEA 2016	Importance: may threaten or otherwise render vulnerable to adverse change important habitat
Solar Resource Potential	Perez et al. 2002; Hanser 2004; SEIA 2015	Importance: may threaten or otherwise render vulnerable to adverse change important habitat

Wind Resource Potential	Wind Power Classes, TrueWind Solutions 2003; Hanser 2004; FAA 2015	Importance: may threaten or otherwise render vulnerable to adverse change important habitat
Erosion potential	Linard et al. 2014	Importance: may threaten or otherwise render vulnerable to adverse change important habitat
Aquifer vulnerability to pollution	Linard et al. 2014	Importance: may threaten or otherwise render vulnerable to adverse change important habitat

Following McClure et al. (2017), we determined the values of each of the indicators in the proposed ACEC relative to the surrounding landscape[3] using a simple scoring system based on percentile ranks. This approach enables the quantification of the degree to which characteristics of a proposed ACEC are ***exemplary, distinctive,*** or have ***regional significance***. Specifically, the mean value of each indicator within the proposed ACEC was compared to the distribution of means of a large random sample of areas across four different extents:

1. all lands in the 11 western states (n = 2000)
2. all western lands within the BLM's jurisdiction (n = 2000)
3. all lands within New Mexico (n = 500), and
4. all New Mexico lands within the BLM's jurisdiction (n = 500).

The area of each random sample was equivalent to the area of the proposed ACEC. Scores ranged from 0 to 100. A score of 98 for a given indicator would indicate that the mean value of that indicator in the proposed ACEC was greater than or equal to 98% of equivalently-sized random samples. Although there is inherent variability associated with random sampling, the large sample sizes helped to constrain that variability, and multiple iterations confirmed that indicator rankings were robust.

As a final step, we assessed the degree to which the proposed Otero Mesa ACEC intersects with areas in New Mexico identified as globally important bird areas (IBA) by the National Audubon Society in partnership with BirdLife International (National Audubon Society, 2023).

Results and Discussion

Our analysis indicates that multiple relevance and importance criteria are met within the proposed Otero Mesa ACEC, and further highlights the need for special management of these values and resources.

The proposed Otero Mesa ACEC is exemplary in its ecological intactness and connectivity.

The proposed Otero Mesa ACEC consists of large amounts of land undisturbed by human development. We observed ecological intactness scores in the 82nd, 66th, 82nd and 83rd percentiles compared to other equivalently-sized lands across the West, BLM lands within the West, New Mexico, and BLM lands within New Mexico, respectively (Fig. 2 and Map 2). Landscapes with high ecological intactness are those with

[3] Because Erosion Potential and Aquifer Vulnerability to Pollution are coverages unique to New Mexico, the values for these threat indicators within the proposed ACEC can only be compared to other lands within New Mexico, and not the other western states.

minimal to no influence from human activities, which means they are able to support natural evolutionary and ecological processes (Parrish et al. 2003; McClure et al. 2017). These processes in turn can sustain diverse and healthy communities of organisms and afford a better chance for acclimation and adaptation in the face of ongoing climatic changes and other interacting stressors (Lawler et al. 2015). The lands within the proposed boundary of the Otero Mesa ACEC also support the largest remaining black grama grassland within the Chihuahuan desert as well as a number of rare plant species including the Guadalupe mescalbean, Guadalupe needlegrass, the gray sibara, the cliff nama and the five-flower rockdaisy. The relative lack of significant human development in the proposed ACEC also promotes a high degree of ecological connectivity. Landscapes with high degrees of ecological connectivity support dispersal, migration, gene flow, and range shifts under changing climatic conditions (Dickson et al. 2017; Littlefield et al. 2019). The proposed Otero Mesa ACEC is exemplary in its contribution to ecological connectivity. We observed ecological connectivity scores in the 97th, 98th, 85th, and 84th percentiles compared to other equivalently-sized lands across the West, BLM lands within the West, New Mexico, and BLM lands within New Mexico, respectively (Fig. 2 and Map 2).

The proposed Otero Mesa ACEC is exemplary in its diversity of reptile, amphibian, and mammalian species.

The largely intact and well-connected landscapes within the proposed Otero Mesa ACEC are also exemplary in their vertebrate biodiversity. Relative to other lands across the West, BLM lands within the West, New Mexico, and BLM Lands within New Mexico, the proposed ACEC scores in the 99th, 98th, 90th, and 74th percentiles, respectively, of reptile species richness (Fig. 2 and Map 2), in the 98th, 98th, 88th, and 72nd percentile for amphibian species richness, and in the 97th, 98th, 85th, and 77th percentiles for mammalian species richness (Fig. 2 and Maps 3 and 4). Reptile species including the Western Massasauga (*Sistrurus tergeminus*)[4] and the Mojave rattlesnake (*Crotalus scutulatus scutulatus*)[5], which are both listed as 'vulnerable in New Mexico' by Natural Heritage New Mexico, are known to occur within the proposed ACEC's boundary. The proposed ACEC also contains important habitat that supports healthy herds of important game species including pronghorn antelope (*Antilocapra americana*)[6] and mule deer (*Odocoileus hemionus*)[7], as well as species sensitive to disturbance pressures including the black-tailed prairie dog (*Cynomys ludovicianus ludovicianus*)[8], the spotted bat (*Euderma maculatum*)[9] and the plains leopard frog (*Lithobates blairi*)[10].

The proposed ACEC also covers 82% of the globally important Otero Mesa IBA (National Audubon Society 2023). The IBA is designated due to its role in providing important habitat and breeding areas for burrowing owls, suitable habitat for the endangered aplomado falcon, and its use by migrating grassland birds including the long-billed curlew and the upland sandpiper. The Otero Mesa IBA also provides wintering and migration habitat to a range of species including Baird's sparrow (*Ammodramus bairdii*),

[4] https://bison-m.org/booklet.aspx?SpeciesID=030130
[5] https://bison-m.org/booklet.aspx?SpeciesID=030165
[6] https://bison-m.org/booklet.aspx?SpeciesID=050585
[7] https://bison-m.org/booklet.aspx?SpeciesID=050190
[8] https://bison-m.org/booklet0.aspx?SpeciesID=050200
[9] https://bison-m.org/booklet.aspx?SpeciesID=050095
[10] https://bison-m.org/booklet.aspx?SpeciesID=02004

grasshopper sparrow (*Ammodramus savannarum*), Sprague's pipit, and ferruginous hawk (National Audubon Society 2013). In sum, the total acreage of IBA contained within the proposed Otero Mesa ACEC amounts to approximately 10% of the total IBA area within New Mexico.

The proposed Otero Mesa ACEC may support species that rely on stable climatic conditions, but species elsewhere may be challenged to access those conditions.

Climatically stable areas will have future climates projected to be similar to present conditions. These stable areas can continue to support existing ecological communities adapted to a particular suite of climate conditions while also serving as potential refugia for species tracking suitable climates through time (Williams et al. 2007; Mahony et al. 2017; Carroll 2018). The proposed Otero Mesa ACEC scores within the 78th, 82nd, 79th percentiles for climatic stability compared to the other all lands in the West, all BLM lands in the West, and all lands in New Mexico, respectively (Fig. 2 and Map 5; not shown in Fig. 2a and 2d, as climate stability is not a top indicator relative to all lands in the West and all BLM lands in New Mexico, respectively). While climate stability describes how similar future conditions will be to those in the present, climate velocity is a metric that represents the speed and direction a species must migrate to track the same climatic conditions over time as the climate changes (Loarie et al. 2009; Brito-Morales et al. 2018). Low regional velocities, therefore, correspond to accessible climatic conditions, which may afford climatic refugia or stepping-stones for species in a warming world (Morelli et al. 2020). The proposed Otero Mesa ACEC scores within the 49th, 51st, 25th, and 30th percentiles for climate accessibility relative to other equivalently-sized areas in the West, western BLM lands, New Mexico, and New Mexico BLM lands, respectively. This suggests that while the climate in the area will be relatively stable in the near future, species elsewhere that are reliant on such conditions will be challenged to access them swiftly enough. Well-accepted, evidence-based climate adaptation strategies that can maintain or enhance the existing connectivity of local and regional landscapes including the proposed ACEC (e.g., Stein et al. 2014) can reduce non-climate stresses (e.g., disturbances associated with energy development, invasive species), facilitate natural processes by protecting diverse ecological and geophysical attributes, and protect key ecosystem features (e.g., seasonal wetlands, irreplaceable species), which could simultaneously be implemented through ACEC designation of this area.

The proposed Otero Mesa ACEC is vulnerable to adverse change associated with mineral and energy resource development.

The proposed Otero Mesa ACEC is vulnerable to adverse changes associated with both mineral and energy resource development, more so than other regions. Relative to equivalently-sized areas across the West, western BLM lands, New Mexico, and New Mexico BLM lands, the area scores within the 83rd, 81st, 92nd, and 92nd percentiles, respectively, for mineral resource development (Fig. 2). The proposed Otero Mesa ACEC also exhibits comparatively high potential for renewable energy development. Specifically, the area scores within the 80th, 85th, 71st, and 72nd percentiles for wind resource potential and the 91st, 96th, 70th, and 69th percentiles for solar resource potential relative to the West, western BLM lands, New Mexico, and New Mexico BLM lands, respectively (Fig. 2, Map 6). Oil and gas resource occurrence potential in the area has also been assessed to be moderate to high (BLM 2017), suggesting future development pressures. The potential impacts of mineral and energy developments on wildlife species—whether conventional or renewable—are well documented (Jones, ed. 2012; Northrup and Wittemyer 2013). Special management attention will be needed to avoid negative effects on sensitive wildlife species and habitats, which may include habitat loss or fragmentation, direct mortality from vehicle or infrastructure collisions, and reduced individual fitness due to persistent stressors such as noise and light.

Conclusions

In conclusion, our results suggest that the proposed Otero Mesa ACEC meets multiple relevance and importance criteria. The proposed ACEC constitutes a ***significant wildlife resource*** and supports ***natural systems and processes*** through its largely intact landscapes that support high degrees of ecological connectivity and high numbers of amphibian, reptile, and mammal species. In addition, the proposed ACEC almost entirely encompasses the globally important Otero Mesa IBA. The proposed ACEC also features high degrees of climatic stability. Combined, landscape connectivity and climatic stability afford important climate adaptation potential by enabling species to both move and adapt in place as temperatures rise and precipitation patterns shift. This climate stability potential alone is of ***special worth*** and warrants special management considerations. Our analyses demonstrate the ***regional (i.e., more than local) significance and exemplary nature of these values*** as compared to other places in the West, and thus underscores that the proposed ACEC warrants special management to protect these values. Finally, our analysis highlights the proposed ACECs' ***vulnerability to adverse change*** related to the threat of future development of mineral and energy resources. Designation of this unit as an ACEC and implementing proactive mitigation measures would safeguard the significant ecological value of these lands—particularly under changing climatic conditions—and prevent their degradation through extractive uses while protecting the intactness of the important desert and grassland ecosystems supported by this landscape.

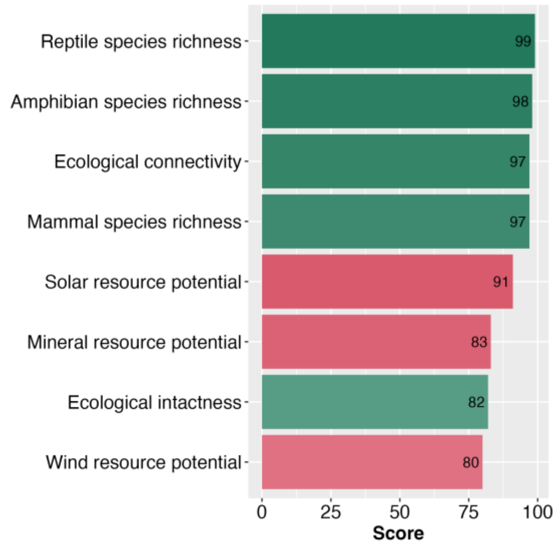


Figure 2a. *West-wide comparison*: The top eight scoring indicators of 23 that convey ACEC relevance, importance and threats. Values for the proposed Otero Mesa ACEC were compared to a random sample (*n* = 2000) of equivalently sized areas across the 11 western states. Potential scores range from 0-100 (100 being the greatest).

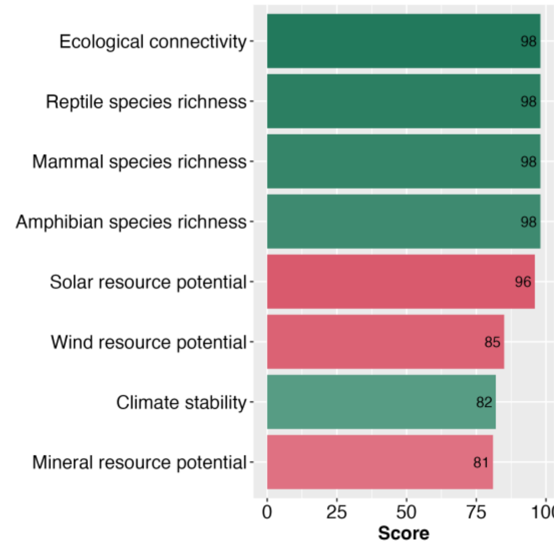


Figure 2b. *Comparison to western BLM lands:* The top eight scoring indicators of 23 that convey ACEC relevance, importance and threats. Values for the proposed Otero Mesa ACEC were compared to a random sample (n = 2000) of equivalently sized areas across BLM lands in the 11 western states. Potential scores range from 0-100 (100 being the greatest).

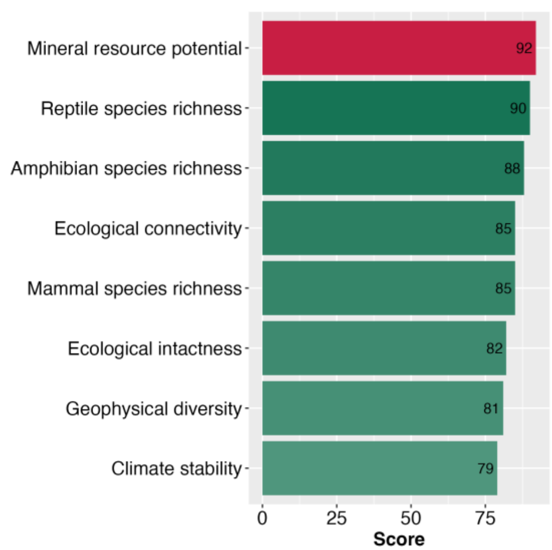


Figure 2c. *Comparison to New Mexico:* The top eight scoring indicators of 23 that convey ACEC relevance, importance and threats. Values for the proposed Otero Mesa ACEC were compared to a random sample (n = 500) of equivalently sized areas in New Mexico. Potential scores range from 0-100 (100 being the greatest).

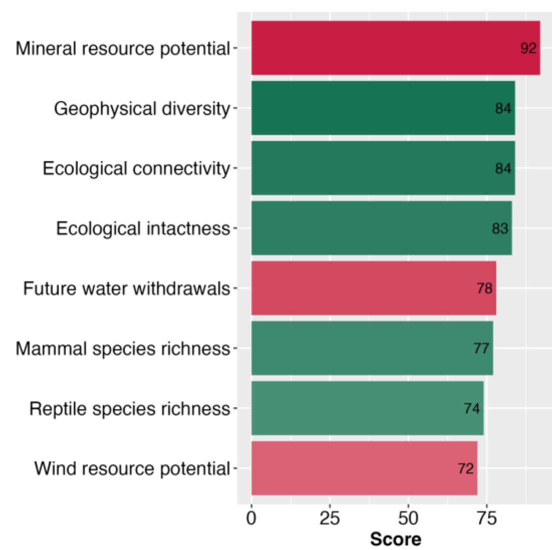
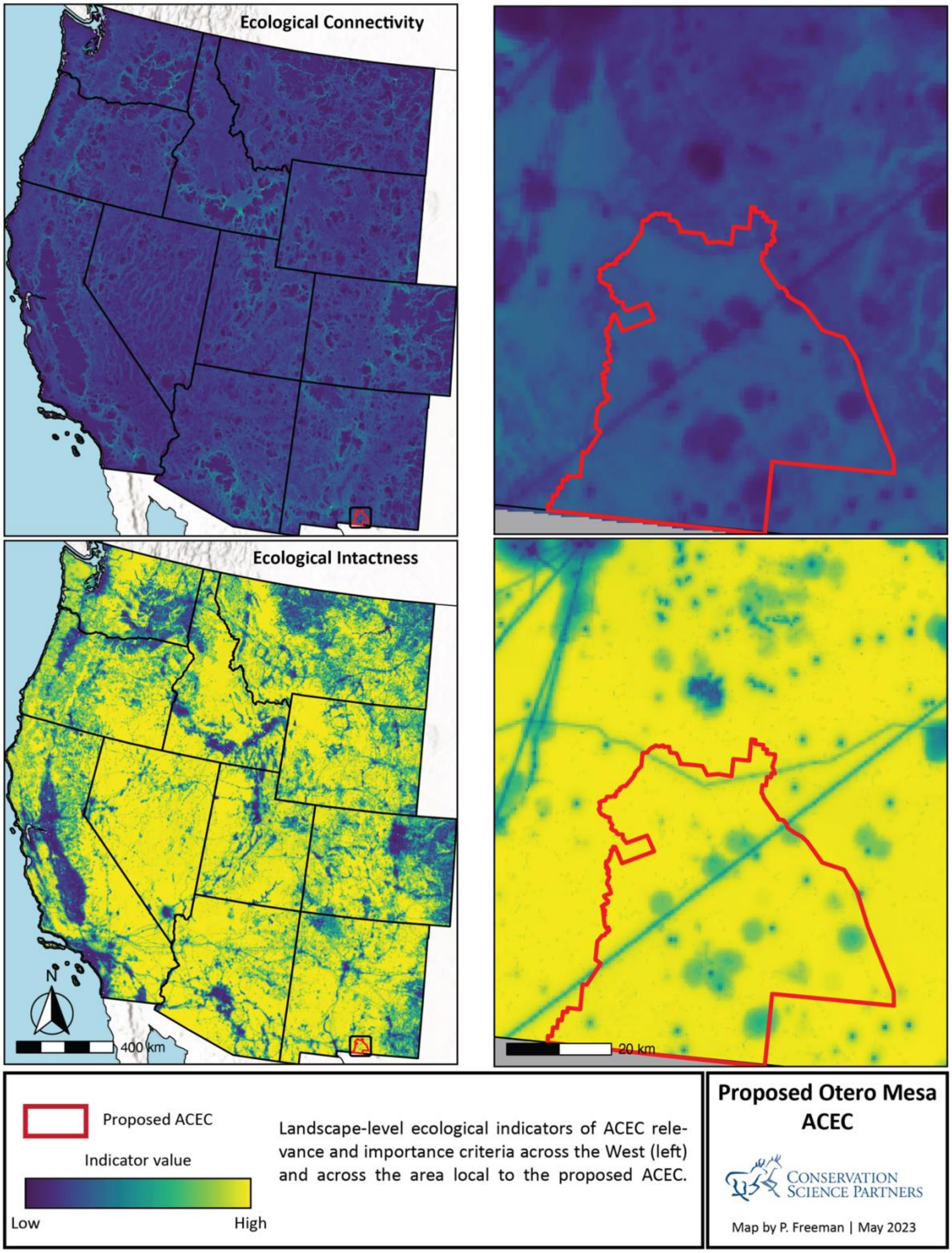
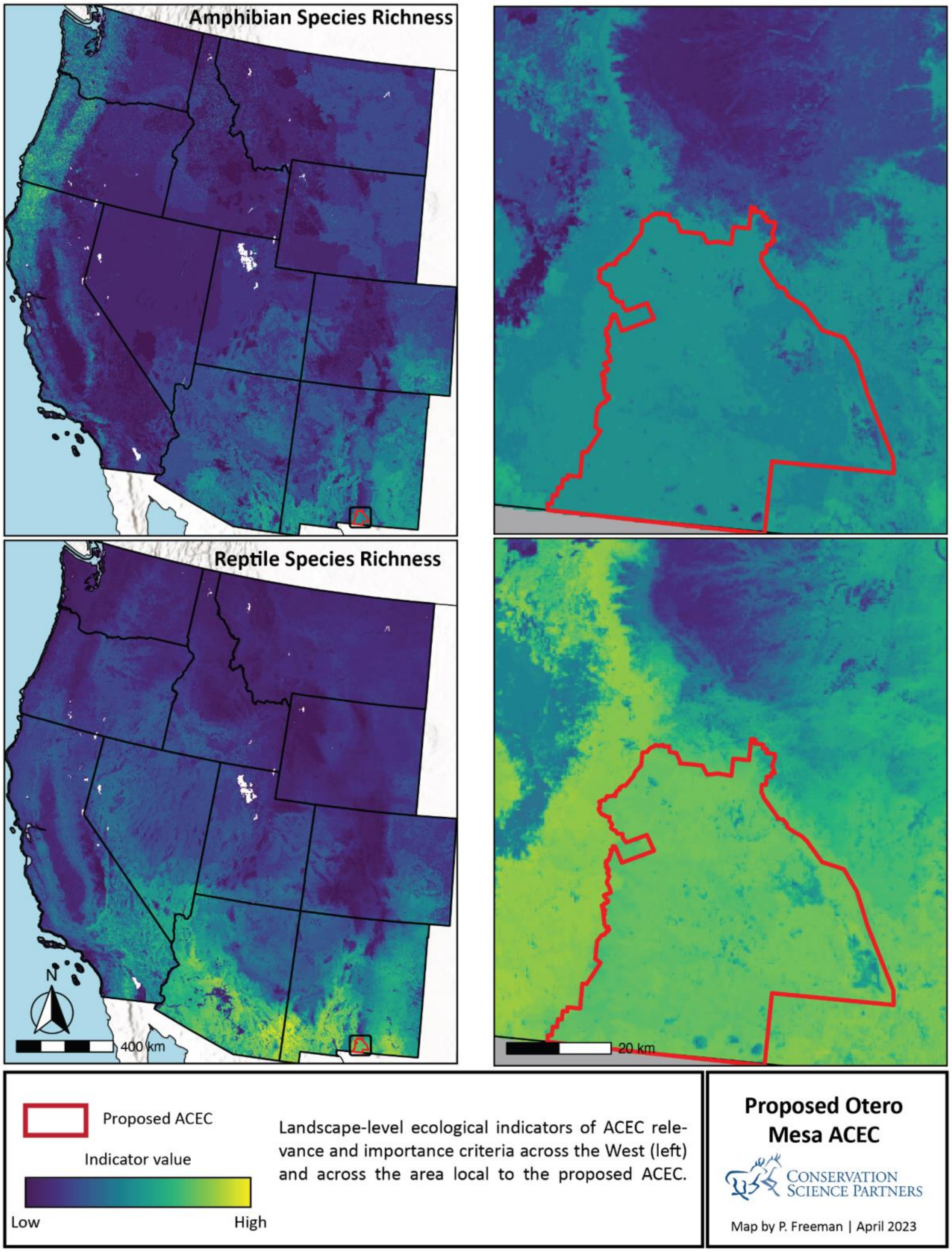


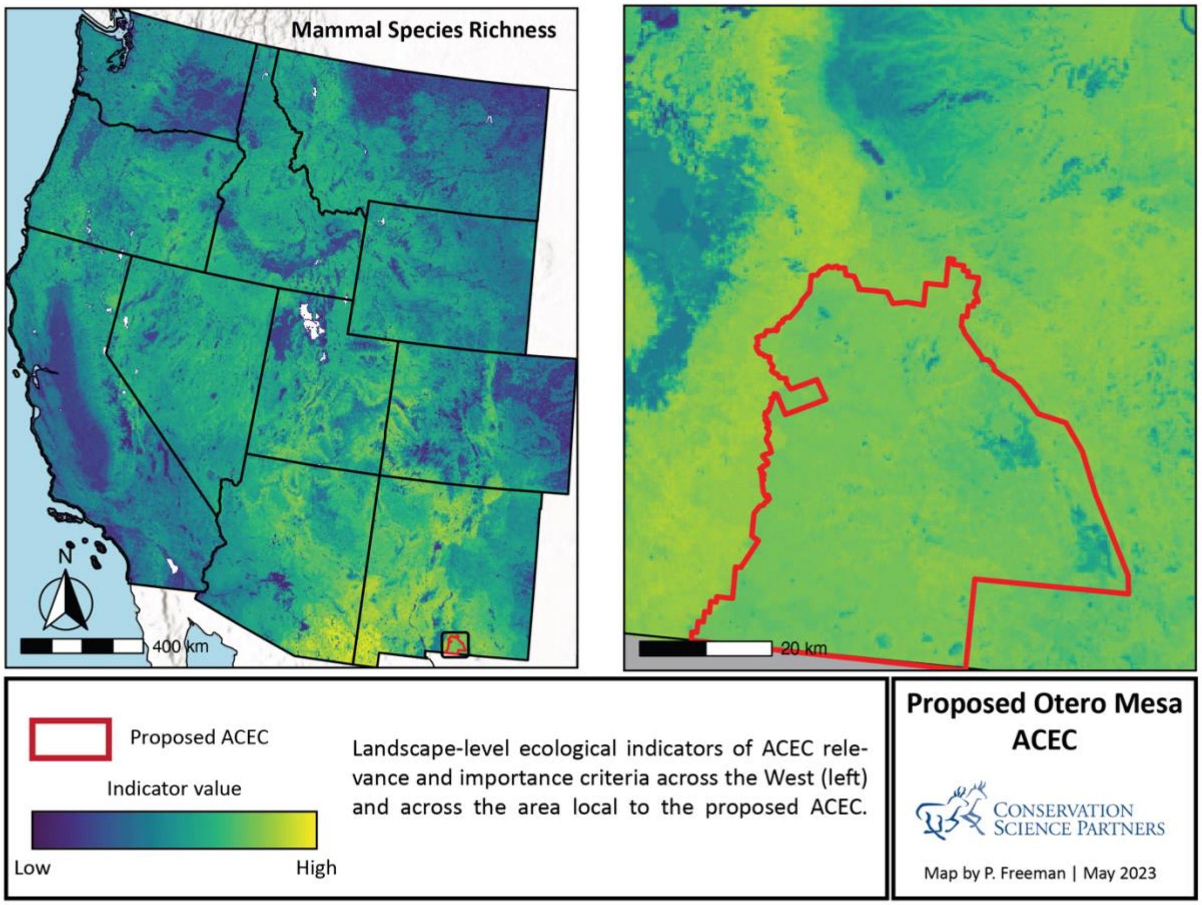
Figure 2d. *Comparison to New Mexico BLM lands:* The top eight scoring indicators of 23 that convey ACEC relevance, importance and threats. Values for the proposed Otero Mesa ACEC were compared to a random sample (n = 500) of equivalently sized areas across BLM lands in New Mexico. Potential scores range from 0-100 (100 being the greatest).



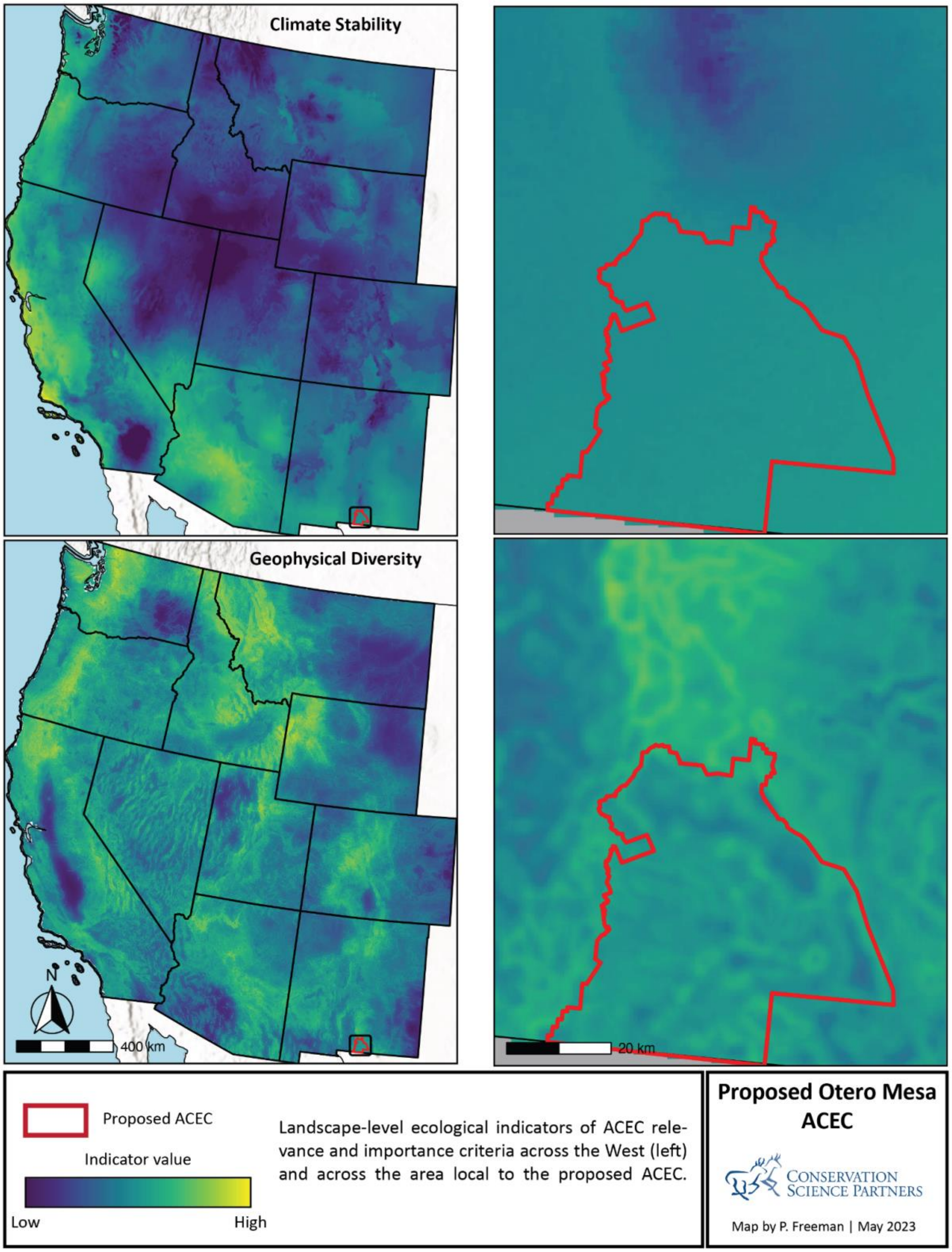
Map 2. ACEC Relevance and Importance Criteria Indicators – ecological connectivity (upper) and ecological intactness (lower).



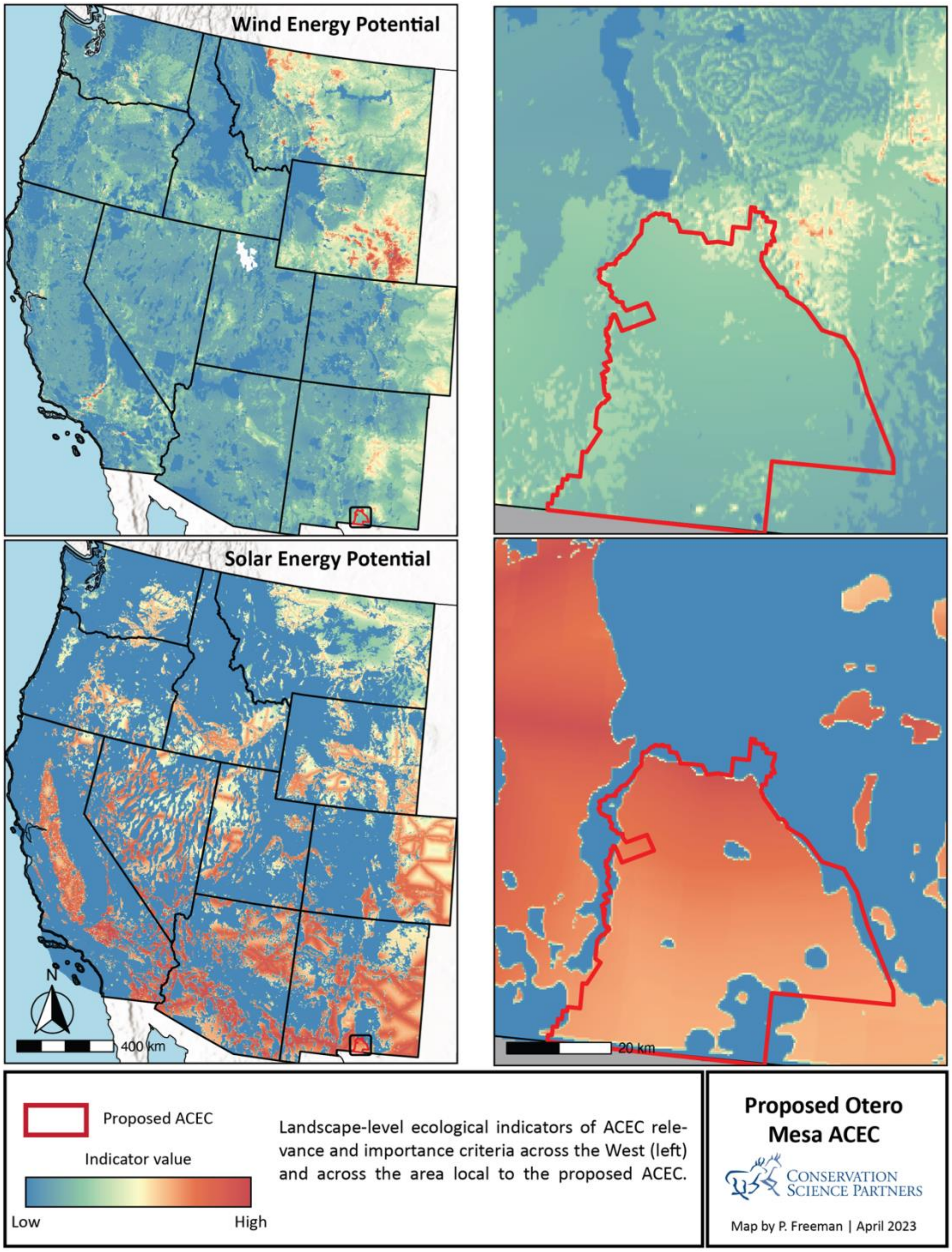
Map 3. ACEC Relevance and Importance Criteria Indicators – amphibian species richness (upper) and reptile species richness (lower).



Map 4. ACEC Relevance and Importance Criteria Indicator – mammal species richness.



Map 5. ACEC Relevance and Importance Criteria Indicators – climate stability (upper) and geophysical diversity (lower).



Map 6. ACEC Relevance and Importance Criteria Indicators – wind energy potential (upper) and solar energy potential (lower).

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Appendix 1. Derivation of Indicators

Descriptions of source data and derivation methods for ecological indicators to characterize the values and threats within the proposed ACEC.

Values

Climate accessibility. Estimates the degree to which the current climate conditions in a given location will be accessible in the future. Areas of high climate accessibility are those that contribute to the ability of organisms to adapt to climate change through both local and long-distance movements (Carroll et al. 2015). Climate accessibility was derived as the multiplicative inverse of climate velocity (i.e., -1*climate velocity), a measure of the instantaneous velocity of climate change at a given location. The climate velocity metric used here was developed at 1-km resolution by Hamann et al. (2015) by integrating 11 climate variables via principal component analysis (PCA; see Hamann et al. 2015 for details on climate variables—9 are described in the paper though 11 are provided on Databasin, from which the data were retrieved) and calculating velocity based on the distance between sites with matching present climate conditions (averaged from 1981 to 2010) and future climate conditions (2055) under Representative Concentration Pathway (RCP) 8.5 (IPCC 2014). The Hamann et al. (2015) algorithm can be implemented in either forward (finding future climate locations that match the focal location's current climate) or backward (finding current climate locations that match the focal location's future climate) directions. We derived our estimate of climate accessibility based on backward velocity, which asks: given the projected future climate conditions of a focal location, what is the minimum distance an organism has to migrate in order to colonize the focal location from another location with similar present day climate?

Climate stability describes the similarity between present climate (averaged between 1981 and 2010) and future climate (2055) at a given location. Climatically stable areas will have future climates that are similar to present conditions. Our estimate of climate stability was derived as the multiplicative inverse of climatic dissimilarity (Williams et al. 2007; Carroll 2018), with dissimilarity being a frequently used metric to estimate how different the future climate at a given location will be from its present climate conditions (Mahony et al. 2017). This dissimilarity metric is based on 11 climate variables integrated via PCA (Belote et al. 2018). Multivariate local climate dissimilarity (LCD) is calculated as

$$\text{LCD} = \sqrt{\left(PC1_{future} - PC1_{current}\right)^2 + \left(PC2_{future} - PC2_{current}\right)^2}$$

where PC1 is strongly associated with temperature and PC2 is strongly associated with precipitation and moisture variables (Belote et al. 2018).

Ecological connectivity estimates the ability of a given location to support the natural movement of organisms through processes such as dispersal, migration, and gene flow, and to provide linkages between areas of high-quality habitat (Dickson et al. 2017). Maintaining areas of high ecological connectivity is also considered a key strategy for supporting species migrations and range shifts under climate change (Heller & Zavaleta 2009; Littlefield et al. 2019). We used the procedure described by Dickson et al. (2017) to derive resistance surfaces for connectivity models by rescaling our anthropogenic impact layers for conterminous United States (CONUS) and incorporating a modest penalty for steep slopes (Dickson et al. 2017), which may present barriers to movement for many terrestrial organisms. We used mammal species richness layers to estimate source strength (the likelihood that a given location will act as starting/end point for animal movement), and treated source strength as proportional to the number of mammal species estimated to occur in a given location. We estimated mammal richness by overlaying International Union for Conservation of Nature (IUCN) range maps for mammals (408 species) and restricted these ranges based on recently published maps of IUCN habitat (Jung et al. 2020). Richness maps for CONUS were produced at 2-km resolution, as recommended for IUCN range data. We used a circuit theory-based approach (McRae et al. 2008; Dickson et al. 2019) to model the flow of organisms across CONUS and Alaska, using Omniscape software (Landau et al. 2021) to implement omni-directional connectivity models for each extent at 1-km resolution (after McRae et al. 2016).

Ecological intactness estimates the degree to which a given location remains in a natural state (i.e., unmodified by human land use). Ecologically intact landscapes are those with minimal or no influence from human activities and which are therefore able to support natural evolutionary and ecological processes (Parrish et al. 2003) as well as communities of organisms similar in species composition, diversity, and functional organization to those of undisturbed habitats (Parrish et al. 2003). We calculated ecological intactness as *1 - AI*, where *AI* is the degree of anthropogenic impact on a landscape. Drawing on our previous work (CSP 2019, see also Theobald 2013), we derived estimates of anthropogenic impact at 90-m resolution for CONUS (circa 2017), quantifying the intensity and extent of multiple human activities, including residential and commercial development, agriculture, energy production and mining, transportation, and forestry (CSP 2019).

Ecological System Diversity. Diverse ecological systems, defined as a "group of plant community types that tend to co-occur within landscapes with similar ecological processes, substrates and/or environmental gradients" (Comer et al. 2003), provide a variety of habitats essential for maintaining species diversity (Noss 1990). Ecological system diversity may stem from the presence of diverse vegetation types, strong elevation gradients, ecotonal transitions among biome types, and/or interspersion of unique water-associated communities, such as wetlands, marshlands, meadows, and riparian zones. We followed methods in Theobald et al. (2015) to derive an estimate of ecological systems diversity at multiple spatial scales, equivalent to average sizes (1.2 – 115.8 km radii) of HUC 4-16 watersheds and using the Shannon-Weiner Equitability Index. We used the 30-m resolution USGS Gap Ecological Systems Units (USGS 2011) as the basis for calculating ecosystem diversity and assigned null values to all developed and invasive species land cover types prior to running the analysis, so that these lands would not contribute toward the diversity calculation.

Ecological System Rarity. Areas with high ecological system rarity are those that support rare, unique, or irreplaceable natural systems. These systems are likely to consist of species that are rare, unique, or irreplaceable. Ecological systems are defined as a "group of plant community types that tend to co-occur within landscapes with similar ecological processes, substrates and/or environmental gradients" (Comer et al. 2003), thus they incorporate physical components such as landform position, substrates, hydrology, and climate in addition to vegetation. To characterize ecological system type rarity, we calculated the areal extent of USGS GAP ecological system types at 30-m resolution (USGS 2011), then normalized the values based on the maximum value so that they ranged from 0 (least rare) to 1 (most rare).

Imperiled Species Richness estimates the total number of imperiled species likely to occur in a given area. For CONUS, we used a model of imperiled species richness (NatureServe 2020). This layer integrates habitat suitability maps for 2,216 of the nation's most imperiled species, including vertebrates (birds, mammals, amphibians, reptiles, freshwater fishes; 309 species), freshwater invertebrates (228 species), pollinators (43 species), and vascular plants (1,636 species). The 990-m resolution layer includes species designated by NatureServe as imperiled or critically imperiled, and species listed as threatened and endangered under the Endangered Species Act.

Vertebrate Diversity. We used published data on amphibian, bird, mammal, and reptile species richness from the USGS Gap Analysis Project (USGS 2019). These data are based on habitat distribution models for 1,590 species present in CONUS. Species models were overlaid to generate richness maps (30m resolution). (Gergely et al. 2019).

Geophysical Diversity. Unique geophysical units can be defined based on combinations of lithology and landform, i.e., the composition of rock and soil materials combined with their relative position in the landscape (e.g., ridge, slope, valley). High geophysical diversity is associated with high levels of genetic and species diversity (Lawler et al. 2015) as well as species endemism (Davis et al. 2008). Furthermore, diverse geophysical settings offer local heterogeneity and refugia that are expected to be critical to species persistence and maintenance of biodiversity under climate change (Ackerly et al. 2010; Beier & Brost 2010). To characterize geophysical diversity, we used a published model of physiographic diversity (Theobald et al. 2015) that characterizes unique geophysical units based on an overlay of landforms and surficial lithology. In this model, diversity is calculated using Shannon-Wiener Equitability Index and at multiple spatial scales, equivalent to average sizes (1.2 – 115.8 km radii) of HUC 4-16 watersheds. Indices derived at multiple scales were then combined to produce a single multi-scale index at 30-m resolution.

Geophysical Rarity. Ensuring the protection of a regionally diverse array of geophysical settings, including the rarest features, is an important strategy both for conserving a variety of species, as well as ecological and evolutionary processes such as species diversification, particularly in the face of climate change (Lawler et al. 2015). As described above (see Geophysical Diversity), unique geophysical types that are likely to offer unique habitat conditions can be defined by combining landform (e.g., ridge, slope, valley) and lithology (i.e., soil parent material). To characterize geophysical type rarity, we calculated the areal extent of each of 188 unique geophysical unit types at 30-m resolution based on an overlay of landforms and surficial lithology (Theobald et al. 2015) across the western US, then normalized the values based on the maximum value so that they ranged from 0 (least rare) to 1 (most rare).

Surface Water Availability. Surface water is a critical resource for fish and wildlife and is considered an essential habitat element for maintaining species diversity. Availability of surface water is likely to be a limiting factor for species diversity in arid environments. Water sources in water-limited areas are likely to support unique biodiversity elements such as riparian-obligate species. We characterized the areal extent of surface water into a surface water availability metric by first extracting water features (springs, seeps, perennial rivers, perennial lakes and ponds from the National Hydrography Dataset (1:24,000) (USGS 2008a), then merging and converting water features to 30-meter resolution raster data.

Night Sky Darkness. Places with high night sky darkness have low levels of light pollution, which confers high scenic value. The absence of night light pollution is also likely to indicate low levels of human activity and disturbance in these areas. We used an existing dataset representing the presence of artificial nighttime lights at 740-m resolution observed via satellite (NOAA 2012).

Threats

Future Water Withdrawals. Increasing water demands and resulting predicted future water withdrawals threaten species and systems dependent on these water sources, particularly in water-limited areas. We used published model predictions of future water withdrawals (Brown et al. 2013) to characterize threats to perennial streams and rivers from future water withdrawals at a sub-regional scale (n = 98 regions across the US). The model characterizes projected changes in water withdrawals associated with trends in climate change (A1B scenario), projected water demands, and projected water use efficiencies. We attributed values from this model to all perennial streamlines (1:24,000) (USGS 2008a) and applied an inverse distance squared decay function to account for impacts to waters and surrounding riparian areas.

Mineral Resource Potential. Extraction of mineral resources has both direct and indirect impacts on organisms and their environments, including physical alteration of landform, drainage, and soil conditions, as well as alteration of chemical conditions through waste runoff (Ratcliffe 1974). We used mineral and mine occurrence data from the USGS Mineral Resources Data System (USGS 2005) to characterize mineral resource potential. We generated a binary raster surface based on the presence/absence of mineral occurrences within each 270 m cell and smoothed the data by calculating a focal mean based on a 2-cell (540 m) circular radius around each occurrence. We assigned a value of 0 to open waters, developed (urban) land cover types (USGS 2011), and those classified as protected areas (IUCN I-IV, USGS 2012), because development is unlikely to occur in these areas.

Potential for Oil & Gas Development. The potential impacts of oil and gas developments on wildlife species are well documented (Northrup & Wittemyer 2013). In light of these potential impacts, special management attention will be needed to avoid negative effects on sensitive wildlife species and habitats, which may include habitat loss or fragmentation, direct mortality from vehicle or infrastructure collisions, changes in the fitness of individuals due to anthropogenic disturbances such as noise or light, or increases in predation mortality (Northrup & Wittemyer 2013). We combined two existing datasets to develop a west-wide representation of relative oil and gas resource potential at 1-km resolution because no comprehensive dataset existed for the entire study extent. These included 1) a published predictive model of relative oil and gas resource potential that was conditioned on a suite of geophysical variables and oil and gas well production data (Copeland et al. 2009), and 2) spatial data from the Energy Policy and Conservation Act (EPCA) Phase I-III inventories of oil and gas resources (USDOI et al. 2008), which provides coarse- scale estimates of total oil and gas densities within specific focal basins and extrapolates estimates to unstudied basins. Because the former dataset provided continuous and finer-scaled data, and because this model included a validation, we used this dataset preferentially; however, it excluded California and Washington, as well as parts of New Mexico, Idaho, Montana, and Oregon. We supplemented these gaps, which, with the exception of some areas in California and New Mexico, had low oil and gas resource potential, using the EPCA data. Because the EPCA data characterizes oil and gas potential separately, we generated raster surfaces for each of these resources individually, and as with the solar datasets, took the maximum value of the two at each pixel to represent the resource value (oil vs gas) that was greatest, then max-normalized the result. We visually compared the Copeland et al. (2009) and composite EPCA datasets and verified that areas of maximum resource potential were consistent between them. We then replaced null values in the Copeland et al. (2009) dataset with the composite EPCA data (both max-normalized on a scale of 0 to 1) to generate a wall-to-wall estimate for the entire study extent. Finally, we assigned a value of 0 to open waters, developed (urban) land cover types (USGS 2011), and those classified as protected areas (IUCN I-IV, USGS 2012), because development is unlikely to occur in these areas.

Potential for Solar, Wind, and Geothermal Development. The potential impacts of renewable energy developments such as wind, solar, and geothermal on wildlife species are well documented (Jones, ed. 2012, Northrup & Wittemyer 2013). In light of these potential impacts, special management attention will be needed to avoid negative effects on sensitive wildlife species and habitats, which may include habitat loss or fragmentation, direct mortality from vehicle or infrastructure collisions, changes in the fitness of individuals due to anthropogenic disturbances such as noise or light, or increases in predation mortality (Northrup & Wittemyer 2013). We derived datasets characterizing renewable development potential using data on resource availability, slope, powerline locations, locations of existing facilities, protected areas, and land cover. We used two solar radiation datasets available from the National Renewable Energy Lab (NREL, Perez et al. 2002): Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI). The former is most relevant to siting photovoltaic solar installations, while the latter is more useful for siting concentrating solar installations. We max-normalized each dataset so that values ranged between 0 and 1 and then took the maximum value of these two datasets at each 10-km pixel to represent the value (DNI vs GHI) for which the pixel was most suitable. For wind, we mosaicked the state-by-state wind power resource at 50 m hub height datasets available from NREL (TrueWind Solutions 2003) at 200-m resolution. For geothermal, we used a geothermal resource favorability model derived at 1-km resolution for the western US (USGS 2008b). We calculated the Euclidian distance of each pixel from existing major powerlines (Hanser 2004), and used locations of existing large (> 50 MW) solar installations (n= 53; SEIA 2015), wind turbines (n > 35,000, FAA 2015), and geothermal projects (n = 319, GEA 2016) to fit a distance decay model to characterize resource potential for each renewable type based on distance of existing facilities from powerlines. We multiplied the distance decay model for each renewable type by its resource availability dataset and assigned a value of 0 to all pixels that were beyond a slope threshold (solar = 5%, geothermal =10%, wind = 30%), classified as open water or developed (urban) land cover types (USGS 2011), or classified as protected areas (IUCN I-IV, USGS 2012) since development is unlikely to occur in any of these places.

Erosion potential. Soil erosion is a natural process that is affected by topography, soil structure, hydrologic regimes. However, human disturbance can alter or exacerbate natural erosion processes. The loss of fertile topsoil is a significant threat to a range of ecosystems globally and is particularly problematic for dryland ecosystems that dominate the Western United States (Duniway et al. 2019). Landscapes with naturally high erosion potential are also susceptible to increased rates of soil loss if disturbed through the construction of energy and transportation infrastructure. We used a dataset describing the erosion potential of all land in New Mexico from an assessment performed by USGS scientists (Linard et al. 2014). Linard et al. (2014) implemented the Renard Universal Soil Loss Equation (RUSLE; Renard 1997) using parameters including rainfall energy, soil erodibility, contributing area, vegetation, and erosion control practices to estimate the mean loss of soil in tons/acre/year across the extent of New Mexico and Colorado at 30m resolution. The original layer was sourced from https://water.usgs.gov/GIS/metadata/usgswrd/XML/ofr2014-1158_co_nm_rusle.xml#stdorder. We resampled the erosion potential layer to 270m resolution using bilinear interpolation.

Aquifer vulnerability. Mineral extraction and energy development can lead to the contamination of local aquifers by industrial chemicals. The degree to which aquifers may be susceptible to this contamination is a product of a number of hydrogeologic factors including topography, soil structure and composition, and hydrologic regimes. We used a dataset describing aquifer vulnerability developed for New Mexico as part of an assessment performed by USGS scientists (Linard et al. 2014) that included an implementation of the DRASTIC modeling framework (Aller et al. 1987). The DRASTIC model implemented by Linard et al. (2014) incorporated parameters including the depth to water, water recharge, aquifer media, soil media, topography, the impact of the vadose zone, and the hydraulic conductivity of the aquifer. These variables were integrated into the DRASTIC index as a weighted sum such that higher values of the index indicate higher values of aquifer vulnerability to contamination from surface sources. The original model, derived at 30-m resolution, was sourced from https://water.usgs.gov/GIS/metadata/usgswrd/XML/ofr2014-1158_co_nm_rusle.xml#stdorder and resampled to 270m resolution using bilinear interpolation.