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# An Ecoregional Conservation Assessment for Forests and Woodlands of the Mogollon Highlands Ecoregion, Northcentral Arizona and Southwestern New Mexico, USA

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**Abstract:** The Mogollon Highlands, Arizona/New Mexico, USA, spans a large biogeographical region of 11 biotic communities, 63 land cover types, and 7 ecoregions. This 11.3 M ha region has high levels of beta diversity across topo-edaphic gradients that span deserts to mountain tops. The main stressors affecting the region's forests and woodlands include climate change, livestock grazing, and frequent mechanical removals of large amounts of forest biomass for fire concerns. We present an ecoregion conservation assessment for robust conservation area design that factors in appropriate wildfire response to protect communities from increasing threats of climate-induced wildfires spreading into urban areas. We focused mainly on maintaining connectivity for endangered focal species (grizzly bear (*Ursus arctos horribilis*) and Mexican wolf (*Canis lupus baileyi*)) along with protecting mature and old-growth (MOG) forests, Piñon (*Pinus* spp.)–Juniper (*Juniperous* spp.) Woodlands, and riparian areas. Over half the region is managed by federal agencies where new protected areas can be integrated with tribal co-management and prescribed burning, defensible space, and home hardening to protect communities from the growing threat of climate-induced wildfires. However, just 9% of the study area is currently protected, and even with the inclusion of proposed protected areas, only 24% would be protected, which is below 30 × 30 targets. The potential grizzly bear habitat, wolf habitat connectivity, and MOG forests (1.6 M ha (14.2%) of the study area; 18% protected) are concentrated mainly in the central and eastern portions of the MHE. There were 824 fires (2 to 228,065 ha) from 1984–2021, with 24% overlapping the wildland–urban interface. Regional temperatures have increased by 1.5 °C, with a 16% reduction in precipitation and stream flow since 1970 that under worst-case emission scenarios may increase temperatures another 3 to 8 °C by the century's end. The unique biodiversity of the MHE can be better maintained in a rapidly changing climate via at least a three-fold increase in protected areas, co-management of focal species with tribes, and strategic use of fuel treatments nearest communities.

**Keywords:** ecoregion conservation; mature forests; Mexican wolf; Mogollon Highlands; grizzly bear; riparian; wildland urban interface



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## 1. Introduction

The Mogollon Highlands stretches across >300 km from North Central Arizona to Southwestern New Mexico, USA. It includes seven overlapping ecoregions: Arizona–New Mexico Mountains, Arizona–New Mexico Plateau, Sonoran Desert, Chihuahan Desert, Madrean Archipelago, and Mojave Basin and Range (herein collectively referred to as the Mogollon Highlands Ecoregion (MHE)). Deserts, scrublands, grasslands, forests and woodlands are located within the MHE. However, forests and woodlands are the subject of our assessment.

One of the longest escarpments on the planet traverses the MHE, revealing impressive sedimentary and volcanic formations along its face, with Kaibab limestone and localized karst features capping much of its western extent. The Mogollon Rim rises up to 600 m and forms an ecological and geological transition zone running uniquely northwest to southeast and demarking the southern boundary of the Colorado Plateau with the Basin and Range province in Arizona [1].

The MHE is one of the few places in North America where montane rivers cut through steep-walled sandstone canyons. The largest expanse of Ponderosa pine (*Pinus ponderosa*) forests on Earth is found here [2], and Piñon (*Pinus* spp.)–Juniper (*Juniperus* spp.) Woodlands have high levels of plant richness [1]. Five of the six Rocky Mountain life zones (Lower Sonoran, Upper Sonoran, Transition, Canadian, Hudsonian, and Arctic–Alpine) are present, resulting in exceptional beta diversity traversing the base to the peak of mountain ranges that support high levels of avian richness, plant richness and endemism, and herpetofauna richness and endemism [1]. Portions of the MHE function as important linkage zones or connectivity corridors for the movement of plants and wildlife [1,3] that could also serve in rewilding the Southern Rockies [4]. Landscape connectivity (intactness) is present within the "Gila Bioregion" (the eastern portion of the highlands) that can potentially support the reintroduction of grizzly bears (*Ursus arctos horribilis*) and already supports reintroduced Mexican wolf (*Canis lupus baileyi*) populations [5]. This is also an important biological crossroads (where the Sonoran Desert and Basin and Range intersect red rock country of the Colorado Plateau and Southern Rocky Mountains, resulting in the mixing of flora and fauna from overlapping physiographic provinces [1]. Riparian areas, mature and old-growth (MOG) forests, Piñon–Juniper woodlands, proposed wilderness areas, and federal inventoried roadless areas (IRAs) are recognized conservation priorities [1,6].

Up to half of the MHE annual precipitation occurs during monsoons from late June/early July to mid-September. Monsoon seasons have high variability, with El Niño events channeling high moisture up from the Gulf of Mexico and La Niña bringing drier conditions. Climate change is affecting the greater Southwest region generally through temperature increases, changing precipitation patterns, and projected changes to ecosystems and ecological processes like wildfires [7].

The recent uptick in wildfires, especially those impacting human communities (built environments) within the so-called wildland–urban interface (e.g., a broad zone that can extend out to >2 km from the nearest structure as defined by the Healthy Forest Restoration Act of 2003, PL108-148), has been a major concern of community wildfire protection efforts. These concerns also have led to unprecedented levels of congressional spending on fuel reduction by federal agencies, stepped-up fire suppression in the backcountry (away from towns) [8,9], and flat-out opposition to forest protection proposals by many decision makers [9]. Our objective is to develop an ecoregional conservation assessment (ECA) for the MHE that includes a robust conservation area design in the context of climate change, land uses, and the growing concerns over wildfires. ECAs are useful in setting large-scale conservation priorities based on biodiversity distinctiveness (e.g., biophysical features, richness, and endemism) and status or condition (key stressors and degree of protection) of a place of interest [2]. In this case, we mapped priority conservation areas using GIS and consultation with regional experts. We also incorporated two wide-ranging focal species (Mexican wolf and grizzly bear) that may serve as flagship species for rewilding landscapes. There is increasing interest in the biodiversity importance of this region [1] that thus far has been understudied and undervalued. Thus, our study may be useful as a scientific foundation for conservation planning and increased awareness for addressing its status and condition. Our ECA approach also may be exportable to other portions of the Southwest where conservation proposals have stalled due to similar concerns over wildfires impacting the built environment.

## 2. Study Area

We used EPA Level III ecoregional classifications [10] to map the MHE and overlaid the "Gila Bioregion", a recognized conservation priority [11] within the extreme eastern portion of the study area (Figure 1). The study area boundary was checked by regional experts during a June 2023 online workshop.

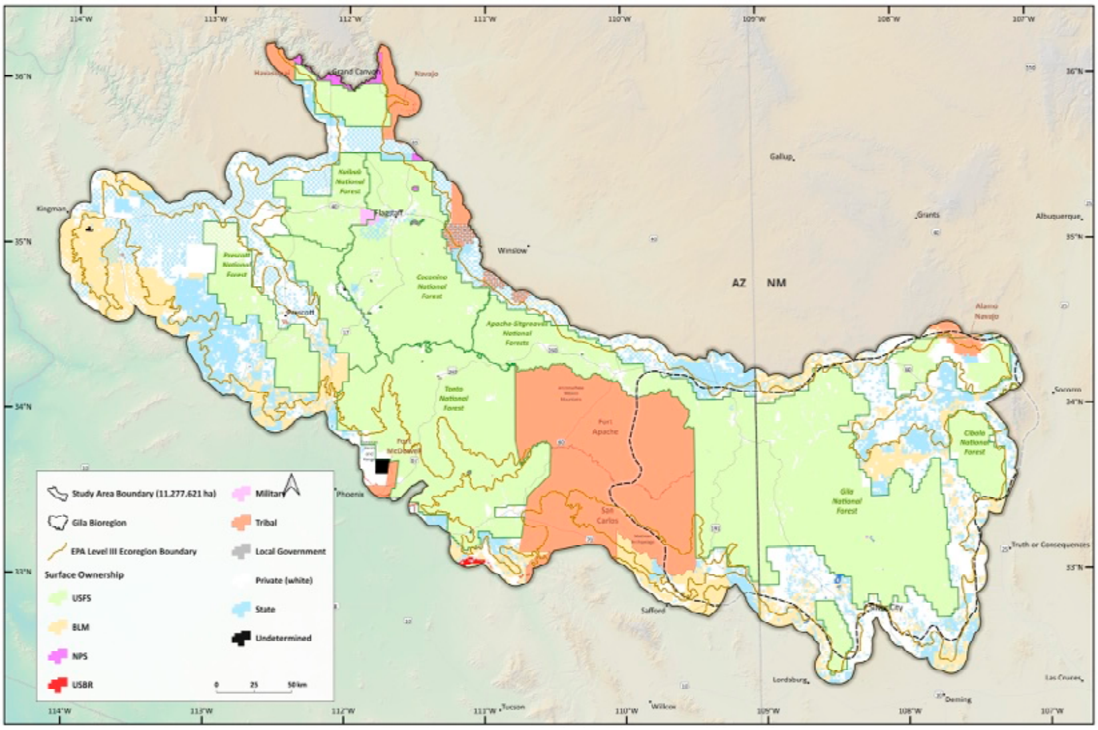


**Figure 1.** Mogollon Highlands Ecoregion, USA, showing land ownerships. The ecoregional boundary is based on EPA Level III classification, with the Gila Bioregion overlaid in the eastern portion.

We clipped all datasets to the study area and re-projected to a CONUS Albers projection (EPSG: 5070) using QGIS version 3.28 [12]. We overlaid the Watershed Boundary Dataset (WBD) Level 8 Hydrologic Unit Codes (HUC) [13] onto the base map. The WBD is a comprehensive aggregated collection of HUC data consistent with national criteria for delineation and resolution. At a minimum, the HUCs are delineated at 1:24,000-scale in the conterminous United States [14].

Based on our mapping approach, the 11.3 M ha MHE includes 11 of 26 biotic communities of the Southwest USA and northwestern Mexico [1]. However, our focus on montane forests, woodlands, and riparian areas is because of the intersection of key stressors like aggressive fire management and livestock grazing. The entire study area is displayed in our analyses to incorporate a climate and connectivity perspective in the ECA approach.

The MHE also includes the WWF's Arizona Mountain Forest #46, considered "regionally outstanding" [2]. Characteristic vegetation in the study area includes Piñon (*Pinus* spp.)–Juniper (*Juniperus* spp.), oak (*Quercus* spp.)–pine woodlands, and Ponderosa pine–Douglas fir (*Pseudotsuga menzeisii*) forests. Additional species include Gambel oak (*Quercus gambelii*), mountain mahogany (*Cercocarpus* spp.), Arizona walnut (*Juglans major*), sycamore (*Platanus occideentalis*), serviceberry (*Amelanchier utahensis*), and bitterbrush (*Purshia tridentata*). Also occurring are Southwestern white pine (*Pinus strobiformis*), lodgepole pine (*Pinus contorta*), white fir (*Abies concolor*), blue spruce (*Picea pungens*), Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and limber pine (*Pinus flexilis*) at upper elevations [13]. Riparian areas are characterized by *Populus* spp. (e.g., cottonwood and aspen) and abundant forbs, grasses, and shrubs in places where livestock densities are reduced.

The Koppen climate classification is Csa: Hot-summer Mediterranean climate. The annual precipitation averages 50 cm, much of which falls as snow in the upper elevations.

## 3. Methods

### 3.1. Landowners and GAP Status

For each state (Arizona and New Mexico) in our study area, we used the surface landownership maps [14] overlaid on the base map. We projected ownership data into QGIS using the GeoPackage format and conducted edits using the procedures from the ASLD Land Status Map Digitizing Procedure guide for Arizona [15] and New Mexico [16]. We downloaded National Forest Boundaries from the U.S. Forest Service Enterprise Data Warehouse [17].

We overlaid the PAD-US 3.0 data for the U.S. Geological Survey (USGS) GAP Analysis Project (GAP) status codes 1–4 on our base map, with GAP 1 and 2 considered "protected" for biodiversity and GAP 3 and 4 not protected [18]. We supplemented these data with the National Conservation Easement Database [19], and we obtained wilderness boundaries from the National Wilderness Preservation System [20] along with BLM Wilderness Study Areas [15,16] and Inventoried Roadless Areas (IRAs; unroaded areas > 2000 ha each) [21]. Notably, IRAs are not considered protected in GAP classifications (e.g., GAP 3) unless they overlap with other protected area categories. However, because they have some level of protection (i.e., most forms of logging are precluded, but not mining) rather than managed for "multiple use" (GAP 3), we assigned them a GAP 2.5 status as in other studies [6]. We obtained proposed wilderness, roads, cities, and state boundaries from regional conservation groups (e.g., Arizona Wild and WildEarth Guardians), OpenStreet Map [22], and Natural Earth [23]. Importantly, the total area in GAP coverage is about 1.2 M ha less than the total study area because many private lands have no GAP status, resulting in the differences in percent calculations related to each dataset as noted in the tables.

### 3.2. Existing Vegetation Types (2020 Update)

LANDFIRE's (LF) 2020 update (LF 2020) Existing Vegetation Type (EVT) represents the current distribution of the terrestrial ecological systems classification developed by NatureServe for the western hemisphere [24]. In this context, a terrestrial ecological system is defined as a group of plant community types that have similar processes, substrates, and/or environmental gradients. EVT also includes ruderal or semi-natural vegetation types within the U.S. National Vegetation Classification (NVC). We displayed these raster data on the base map with a 30 m pixel resolution.

### 3.3. Mature and Old-Growth (MOG) Forests

We obtained spatial datasets on MOG distributions from a published national dataset that used three proxies to define MOG forests derived from LiDAR at a 30 m pixel resolution: tree height, canopy coverage, and above-ground biomass [6]. It is likely that this dataset underestimates the amount of MOG forests in the region because it is based on crown closure as one of the key proxies, yet dry forests contain more open canopies in this region.

### 3.4. Mexican Wolf Connectivity and Grizzly Bear Potential Habitat

For the grizzly bear mapping, we georeferenced and digitized polygons from a published grizzly bear potential map [25]. For the wolf, we used an analysis from 2018 that was based on Circuitscape [26] and Linkage Mapper [27] with a custom resistance surface to identify potential habitat corridors. Linkage Mapper provides a pathway analysis used to identify potential core areas based on their relative connectivity values for each grid cell. The opposite of that is "resistance", where features are identified that would impede movements.

### 3.5. Wildland Urban Interface (WUI) and Wildfires

We used data from each of the eleven National Forests in the Southwestern Region (Region 3) to delineate the WUI using various digitized map sources. Each National Forest makes WUI determinations during National Environmental Policy (NEPA) analysis or on potential status as interpreted by fire analysts. Therefore, the appearance of the WUI projects across the region are not uniform. At the regional level, we appended the WUI data from the eleven National Forests to create region-wide coverage [28]. We used The Monitoring Trends in Burn Severity (MTBS) Program to assess the frequency, extent, and magnitude (size and severity) of all large wildland fires (including wildfires and prescribed fires) from 1984 to 2021 [29]. All reported fires > 400 ha in the western USA were mapped by MTBS across ownerships, which produced a series of geospatial and tabular data for analysis at a range of spatial, temporal, and thematic scales regarding fire extent and severity. We used this map layer as a vector point shapefile of the location of all currently inventoried fires in the ecoregion and overlaid the WUI onto fire occurrences.

### *3.6. Downscaled Climate Projections*

We obtained climate data on past historical trends from the National Oceanic and Atmospheric Administration (NOAA) portal for weather station data [30]. We used 5 weather stations with the most data available for our study area, including Gila Hot Springs, New Mexico (1693 m asl), and Flagstaff (2106 m asl), Alpine (2442 m asl), Prescott (1636 m asl), and Show Low (1935 m asl), Arizona. Prescott, Flagstaff, and Gila Hot Springs had the most complete datasets for 1970–2022, and 4 of the 5 were chosen in Arizona, which contained the majority of our study area.

In addition to weather station data, historical climate trends were assessed using the gridMET surface meteorological dataset at a 4 km resolution from 1979 to the present. Future trends were assessed from an “ensemble” of 20 Global Circulation Models (GCMs) that were downscaled using Multivariate Adaptive Constructed Analogs (MACA) method version 2 based on a higher (RCP8.5) and lower (RCP4.5) emissions scenario [31]. In general, there is greater uncertainty (i.e., more variation among models) in precipitation projections compared to temperature projections, while short- to medium-term projections (mid-century) have less uncertainty than longer-term (end-of-century) projections.

All projections for the study area were created using the Climate Toolbox online portal [32], which has a collection of web tools visualizing past, present, and future climate, drought, extreme heat, and other relevant metrics for the contiguous U.S. We used a custom polygon input to the online portal in the Climate Toolbox as applied to our study area. To assess vegetation change across the study area, we used the Future Vegetation tool in Climate Toolbox, which provided output from the MC2 Dynamic Vegetation Model [33] using 20 GCMs and a higher emissions scenario (RCP8.5) forced with MACAv2-PRISM data to the 1/24th degree.

## 4. Results

### *4.1. Landownerships and Major Vegetation Groupings*

The vast majority (7,996,002 ha; 71%%) of the 11.3 M ha MHE study area is within Arizona, with the rest (3,282,616 ha; 29%) in New Mexico. Most of the MHE is under U.S. Forest Service management (~5.2 M ha; 46%), followed by private (2.2 M ha; 19.5%), tribal (~1.5 M ha; 13.3%), state (1.3 M ha; 11.5%), Bureau of Land Management (975,252 ha; 8.6%), National Park Service (31,533 ha; 0.30%), and other ownerships (35,171 ha; 0.30%) (see Figure 1).

The MHE includes 63 major vegetation groupings according to LANDFIRE (Supplementary Materials Table S1). Forest and open woodland types totaled 5,633,859 ha (~50%) of the study area, characterized mainly by Piñon–Juniper Woodlands (32.5%) and Ponderosa Pine Forest (17.2%), with much lesser amounts in other vegetation groups (Table 1). Riparian vegetation totaled 48,190 ha (0.43%) of the study area.

**Table 1.** Vegetation groups (forests and woodlands only) and GAP status for the Mogollon Highlands Ecoregion. Vegetation group percentages are based on the total 11.3 M ha study area. GAP percentages are based on total GAP area of 10.1 M ha (most private lands had no GAP coverages, reflecting the differences).

| Vegetation Group | HA (%) | GAP 1 HA (%) | GAP 2 HA (%) | GAP 3 HA (%) | GAP 4 HA (%) |
|---|---|---|---|---|---|
| Ponderosa Pine Forest | 1,736,331 (15.4%) | 135,043 (7.8%) | 27,842 (1.6%) | 1,311,517 (75.5%) | 261,929 (15.1%) |
| Piñon–Juniper Woodlands | 3,285,485 (29.1%) | 302,435 (9.2%) | 65,132 (2.0%) | 2,170,935 (66.1%) | 746,983 (22.7%) |
| Conifer–Oak Forest and Woodland | 389,220 (3.4%) | 53,871 (13.8%) | 9201 (2.4%) | 208,797 (53.6%) | 117,351 (30.2%) |
| Juniper Woodland and Savanna | 41,952 (0.4%) | 1141 (2.7%) | 943 (2.3%) | 25,671 (61.2%) | 14,197 (33.8%) |
| Spruce–Fir Forest and Woodlands | 49,996 (0.4%) | 8639 (17.3%) | 2399 (4.8%) | 19,812 (39.6%) | 19,147 (38.3%) |
| Douglas Fir–Ponderosa Pine–Lodgepole Pine Forest and Woodland | 62,099 (0.6%) | 13,488 (21.7) | 661 (1.1%) | 42,893 (69.1%) | 5056 (8.1%) |
| Aspen Forest Woodland and Parkland | 16,740 (0.2%) | 3840 (22.9%) | 866 (5.2%) | 8177 (48.9%) | 3856 (23.0%) |
| Limber Pine Woodland | 3846 (0.0%) | 1308 (34.0%) | 393 (10.2%) | 2098 (54.6%) | 47 (1.2%) |
| Western Riparian Woodland and Shrubland | 48,190 (0.4%) | 3494 (7.3%) | 1942 (4.0%) | 24,211 (50.2%) | 18,543 (38.5%) |

### *4.2. GAP Status of Vegetation Groups*

Most (90.1%) of the MHE (all vegetation types) is unprotected GAP 3 (6.2 M ha, 61.4%) and 4 (2.9 M ha, 28.7%) status (Figure 2, Supplementary Materials Table S1). With the exception of the Limber Pine Woodland, which had small amounts overall, none of the vegetation groups achieved 30% protection levels (Table 1). For the two most common vegetation types, Piñon–Juniper Woodlands (29.1%) had just 11.2% protected (GAP 1 and 2), while Ponderosa Pine Forest (15.4%) had only 9.4% protected. Although riparian areas were uncommon (0.43%) overall, 11.3% had some level of protection. With stepped-up protections for IRAs (GAP 2.5; 5.7%) along with the addition of proposed Wilderness Areas (820,243 ha; 8.1%) and Wilderness Study Areas (45,407 ha; 0.45%), the level of protection for biodiversity overall would rise to about 24.2%, still below 30% targets (Figure 3).

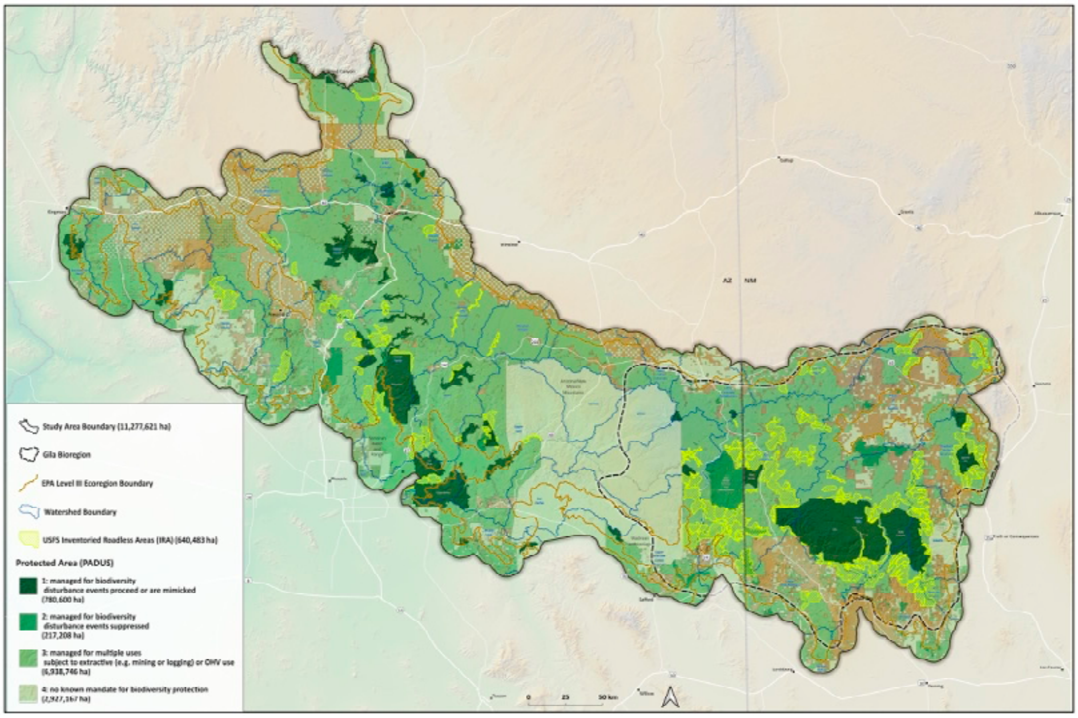


**Figure 2.** Mogollon Highlands Ecoregion showing GAP status.

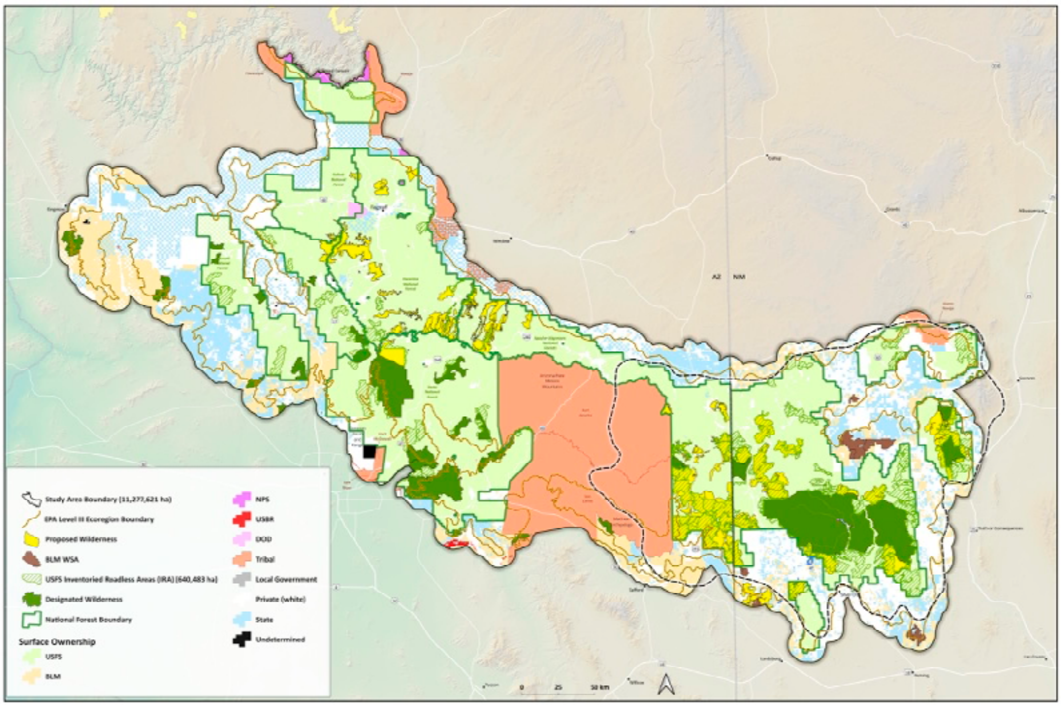


**Figure 3.** Proposed Wilderness and Wilderness Study Areas within the Mogollon Highlands Ecoregion.

### *4.3. Mature and Old-Growth (MOG) Forests*

Approximately 1.6 M ha (14.2%) of the MHE study area contains MOG forests that are concentrated in the central to eastern portions (Figure 4). Tribal lands (22.1%) and the U.S. Forest Service (21.3%) have most (~43%) of the MOG forests, followed by the Department of Defense (19.8%), with the rest on BLM (9.0%), National Park Service (7.6%), and other holdings (1% of each ownership). Of the MOG total, 18% (~288,000 ha) is within GAP 1 and 2 (combined), 12% (191,321 ha) is in IRAs (GAP 2.5), and the rest (69%; 1.1 M ha) is unprotected (Figure 4).

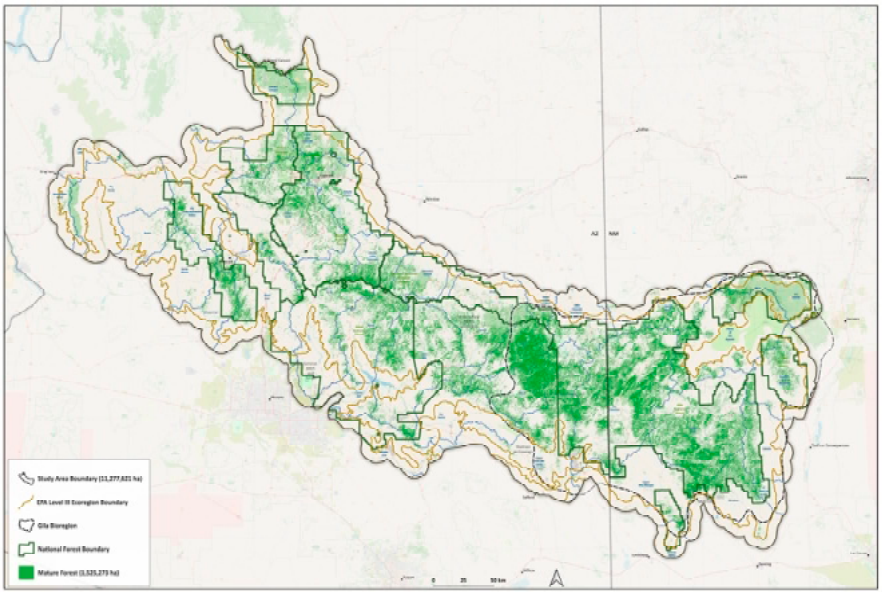


**Figure 4.** Mature and old-growth (MOG) forests within the Mogollon Highlands Ecoregion based on published regional MOG maps [6].

### *4.4. Potential Grizzly Bear Habitat and Mexican Wolf Connectivity*

Approximately 1.5 M ha (13.3%) and 1.6 M ha (14.1%) of high and intermediate grizzly bear habitat suitability, respectively, occurs within the MHE study area, with high suitability concentrated within the eastern Gila bioregion (Figure 5). Habitat suitability increased with higher productivity, remoteness from humans, and characteristics that support movement for grizzly bear restoration and protection [25]. Potential grizzly bear habitat overlaps with key food groups, specifically wapiti (*Cervus canadensis*), fruit-producing shrubs, and acorn-producing oaks. Mexican wolf habitat connectivity is also concentrated in the central portion of the MHE (Figure 6). The highest resistance to wolf habitat connectivity is because of developed areas mainly along the western edge and extreme eastern portion of the mapped region.

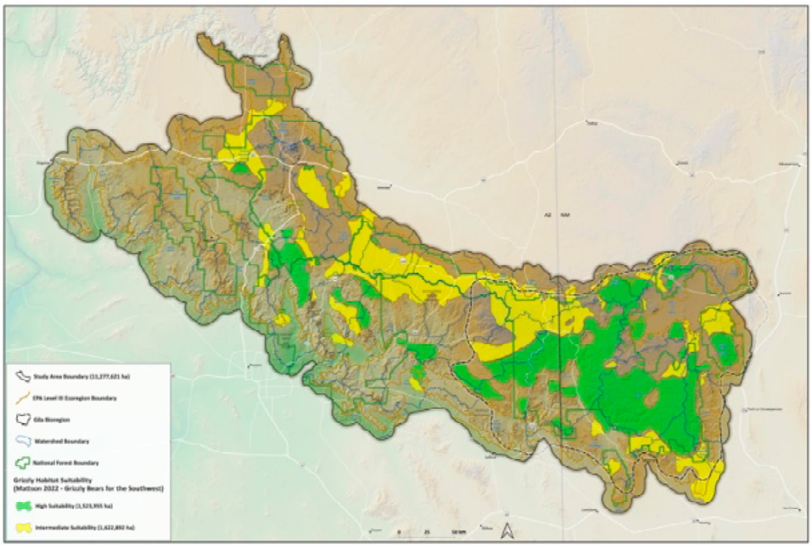


**Figure 5.** Grizzly bear habitat suitability within the Mogollon Highlands Ecoregion based on the grizzly bear potential map [25]. Data were unavailable for the western portion of the study area.

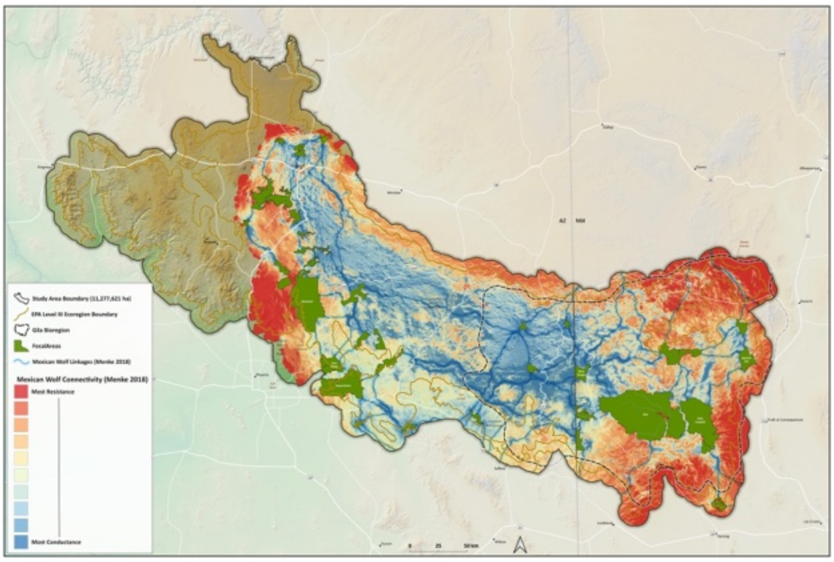


**Figure 6.** Mexican wolf habitat connectivity within the Mogollon Highlands Ecoregion based on an analysis using Circuitscape [26] and Linkage Mapper [27]. Data were unavailable for the western portion. Green areas are designated Wilderness and Wilderness Study Areas considered focal areas for wolf conservation.

### 4.5. Wildland Urban Interface

A total of 820 fire starts were recorded by MTBS within the MHE over the 1984–2021 period, with about 24% of burn perimeters overlapping the WUI boundary (Figure 7). Fire sizes ranged from 2 to 228,065 ha over this period.

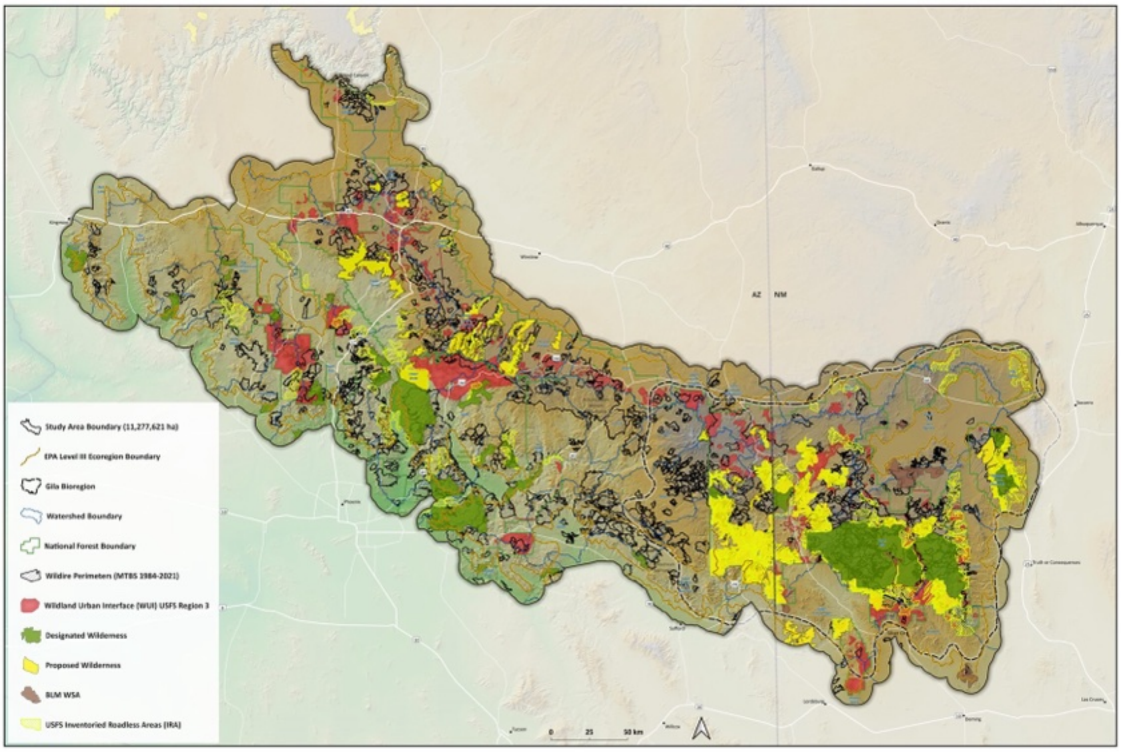


**Figure 7.** Burn perimeters (black) and the Wildland Urban Interface (WUI, in red) within the Mogollon Highlands Ecoregion from 1984–2021 based on the MTBS dataset.

### 4.6. Climate Change Impacts and Projections

The MHE already has experienced a 1.5 °C increase from 1970 to 2022 along with a recorded decline in annual precipitation of 16%, an increase in drought frequency, a decline in snowfall by >30%, and a reduction in river flow by >34% for at least one river, the Verde (Table 2).

**Table 2.** Summary of climate trends for the Mogollon Highlands Ecoregion based on historical (1970–2022) vs. future (2070–2099) for two emissions scenarios (RCP4.5 and 8.5).

| **Historical Trends** [1] | **Projections for 2070-99** [2] | |
|---|---|---|
| 1970–2022 | Lower Emissions (RCP4.5) | Higher Emissions (RCP8.5) |
| Temp. +1.4 °C | Temp. +2 to +4 °C | Temp. +3 to +7 °C |
| Max. temp. +1.2 °C | Max. temp. +2 to +5 °C | Max. temp. +3 to +8 °C |
| Min. temp. +2.2 °C | Min. temp. +1 to +4 °C | Min. temp. +3 to +6 °C |
| +7 days/yr. above 32 °C | +35 days above 32 °C | +64 days above 32 °C |
| – | +15 days above 38 °C | +34 days above 38 °C |
| – | +11 days above 41 °C | +24 days above 41 °C |
| −24 nights < freezing | −14 to −47 nights < freezing | −28 to −68 nights < freezing |
| 16% less precipitation | Precipitation +20% to −11% | Precipitation +47% to −35% |
| Increasing drought [3] | +5 to +31% CWD [4] | +17 to +69% CWD [4] |
| 30–35% reduced snowfall [5] | 40–97% lower SWE [6] | 77–100% lower SWE [6] |
| Verde River flow −34–41% | – | – |

[1] NOAA weather station data at Gila Hot Springs, New Mexico, and Flagstaff, Prescott, Alpine, and Show Low, Arizona; [2] CMIP5 Global Climate Model projections downscaled using MACA (from Climatetoolbox.org, accessed on 20 November 2023); [3] GridMET meteorological dataset accessed through the Drought Stripes Tool in Climatetoolbox.org, accessed on 20 November 2023; [4] Climatic Water Deficit (CWD). [5] Measured at Flagstaff and Show Low, Arizona; [6] snow–water Equivalent (SWE) at Flagstaff and Show Low, Arizona.

Temperature increases by the mid-to-late century will likely worsen within the MHE, the magnitude of which depends on the emissions scenario (lower emissions: +2 to 4 °C vs. higher emissions: +3 to 7 °C) (Supplementary Materials Figures S2 and S3). Notably, by the end of the century, climate projections for the study area show an additional 2 months with extreme temperatures > 32 °C and close to a month > 38 °C and 41 °C if emissions continue at the higher level (RCP8.5) (Supplementary Materials Table S2). However, if emissions follow the lower scenario, severe heat days are cut roughly in half by the end of the century (Supplementary Materials Table S2) as compared to the higher scenario.

Annual precipitation measured at the five weather stations within the study area has varied considerably but with an overall downward trend (Supplementary Materials Figure S3). Likewise, there is uncertainty in future annual precipitation and evapotranspiration rates through 2040–2069 (Supplementary Materials Figures S4 and S5); however, the annual snowfall (Supplementary Materials Figure S6) and snow–water equivalent (Supplementary Materials Figure S7) are each likely to decline drastically. This will greatly impact river flows and riparian vegetation correspondingly. According to the dynamic vegetation model MC2, the climatic envelope of grasslands is likely to increase at the expense of shrubland/woodland (Supplementary Materials Figure S8). Shifts may occur over highly uncertain timeframes that can also be influenced by insect and disease outbreaks, wildfires, drought stress, competition, species-specific dispersal capabilities, and stochastic events that could result in the emergence of novel types. Most notable are the potential impacts to priority vegetation types such as MOG forests and riparian areas.

Finally, changes in climate and vegetation are likely to result in an average increase in the number of days per year with a "high" likelihood of wildfires from 73 (historically) to 78 to 130 by 2040–2069 (Supplementary Materials Figure S9) based on the 100-h fuel moisture projection below the 20th percentile from historic years [34]. Many pine and oak woodlands also have shown extensive dieback and defoliation due to extended droughts and beetles.

## 5. Discussion

### *5.1. Biological Distinctiveness and At-Risk Types*

ECA planning for the MHE in this case study is focused on maintaining the area's biological distinctiveness, mainly for the at-risk forests and woodlands, wide-ranging focal species (including potential habitat for grizzly bears), and landscape features most relevant to connectivity. While untested, our approach may provide a robust conservation strategy that also takes into account wildfire spillover into urban areas and anthropogenic climate change. Importantly, ongoing monitoring, improvements to mapping technologies, and field surveys of priority habitats and focal taxa would provide the necessary data for periodic updates and local conservation planning.

In general, the 11.3 M ha MHE is an ecological "melting pot" of 7 distinct EPA Level III ecoregions, 11 biotic communities [1], and 63 major LANDFIRE cover types. While much of the study area has been transformed by land uses, there is still considerable landscape connectivity as noted by the occurrence of high- and intermediate-potential grizzly bear habitat and Mexican wolf connectivity, particularly in the Gila Bioregion to the east and central portion of the MHE, where large roadless complexes remain. Maintaining connectivity across the five major life zones spanning desert to alpine [1,3–5] would also aid wildlife in search of a suitable habitat in changing climatic conditions. Likewise, much of this need can be enabled by fully protecting intact landscapes such as roadless areas and decommissioning roads in areas important to the two focal species to reduce anthropogenic mortality sinks.

Of the nine forest groups on which we focused, MOG forests in general (14.2%; a subset of all forest groups), Piñon–Juniper Woodlands (29.1%), and riparian woodlands (0.43%) will play a central role in regional conservation. Notably, Piñon–Juniper Woodlands consist mostly of the drought-resistant *Pinus X fallax* [35], and only at the northern extremes does Colorado piñon (*Pinus edulis*) occur along with border piñon (*Pinus discolor)* in the

Gila Bioregion. These woodlands are often Piñon–Juniper chaparral mixes, with abundant and diverse understory chaparral species, such as various oaks, *Garrya wrightii*, *Cercocarpus* spp., and many other Madro-Tertiary tall shrub species.

### *5.2. Landownerships and GAP Status*

Federal agencies (mainly the Forest Service) are responsible for over half of the region, while tribal agencies maintain some 13%. However, the region as a whole and nearly all vegetation groups are at <30% protection levels. Protected-area proposals are mainly focused on maintaining and restoring connectivity for focal species, with the best opportunities largely in the central portion of the MHE and the Gila Bioregion. Additional opportunities for increased protection could come from elevating the GAP status of IRAs (GAP 2.5), especially those clustered in the Gila Bioregion, along with congressional designation of proposed Wilderness and BLM Wilderness Study Areas, which our study reaffirmed as priority conservation areas [12]. At-risk MOG forests can also be protected during national rulemaking as currently proposed by the U.S. Forest Service and the BLM, which may better achieve the minimum 30% targets.

### *5.3. Wildland Urban Interface and Wildfires*

About one-quarter of all fires in the area from 1984 to 2021 intersected the broadly defined WUI boundary, yet most fuel-reduction efforts (e.g., thinning and prescribed burning) generally take place outside the WUI on federal lands [8]. Additionally, wildfires that spill over into urban areas have a tendency to originate on private lands [36] that often emphasize logging for fuel reduction. Under a changing climate, the interaction with land uses is expected to cumulatively effect the loss in regional biodiversity, thereby elevating the importance of integrating conservation, land use practices, and community fire protection together in order to adapt to the emerging novel climate–fire regime [37] while maintaining at least some representation of extant biodiversity in protected areas.

Although very little work has been done on fire regimes in *P. X fallax*, *Juniperus deppeana*, and *J. monosperma* woodlands, we can draw parallels from other *Pinus edulis* or *P. discolor* areas regarding crown fires that are the natural fire cycle, albeit with shorter cycles (~200 years), and a difference likely attributed to the chaparral fuel conditions [38]. Many recent fires in these types appear to be within the historic range of variability [39]. However, within Piñon–Juniper Woodlands, sprouting shrubs may indeed cause type conversions if the fires become too large, and the fire sizes in these woodlands and chaparral types seem to be increasing with the reproduction of conifers waning [40,41]. Ponderosa pine and mixed conifer that had surface fires and some high-severity fire historically (during droughts) now have more crown fires [42–44].

### *5.4. Climate Change and Other Risk Factors*

Much of the Southwest (already a hot and dry place) is trending toward an anthropogenically induced climate of extremes where heat domes and perhaps droughts are increasingly common, with the effects on wildfires amplified by intensive land management practices [6]. Absent comprehensive ecoregional planning and major reductions in GHG emissions across all sectors including land use, the accumulation of stressors will radically transform society, ecosystems, and vulnerable species. In addition, the number of days and nights below freezing will continue to drop, with less snowfall to replenish stream flow, particularly for the Verde River, one of the main rivers traversing our study area. Notably, the Salt River, a major tributary of the Gila River that also runs through our study area, supports extensive riparian and deciduous habitats for rare species like the Southwestern willow flycatcher (*Empidonax trailii extimus*), western yellow-billed cuckoo (*Coccyzus americanus occidentalis*), and Southwestern river otter (*Lontra canadensis sonora*). The Salt River is listed as one of the nation's most endangered [45]. It begins with high-elevation snowmelt that could dissipate this century, further impacting these communities. While this river remains undammed and host to many stretches of intact riparian habitat and outstanding areas of biodiversity, continued diversion, loss of snowpack, and higher temperatures, in addition to invasive species like tamarisk (*Tamarix* spp.), threaten to dewater much of it.

Climatic extremes generally are priming the MHE for larger wildfires, insects, disease, and droughts that will place even more stress on at-risk forests and woodlands, especially MOG and riparian areas. Emphasis on restoring historic fire conditions is often hampered by controversy over how much high-severity fire is within historic bounds, whether historic conditions are even the appropriate baseline in a radically changing climate, and excessive removal of biomass by land managers responding to fire risks far removed from communities, especially large reductions in the understory of forests that may then be prone to excessive drying and weed infestations [9,46].

Numerous forest insects and diseases have been increasing in the MHE, largely attributed to warmer winters, hotter summers, and drought stress [47–49]. These include emory (*Quercus emoryi*) and silverleaf oaks (*Q. hypoleucoides*) affected by *Biscogniauxia* canker and associated drought; piñon ips beetle (*Ips confusus*) outbreaks in piñon pine (*Pinus edulis*); large swaths of *Juniperus osteosperma*, *Juniperus monosperma*, and *Juniperus deppeana* (an iconic regional juniper species) diebacks from drought; Ponderosa pine affected by bark beetle outbreaks magnified by drought; Douglas fir affected by tussock moth (*Orgyia pseudotsugata*) and root rot pockets; spruce beetles (*Dendroctonus* spp.) in some upper elevation forests; and loopers (*Caripeta divisata*) and spruce aphids (*Elatobium abietinum*) associated with warmer winters.

Other risk factors include limber pine (upper-elevation species) that may be especially prone to drought [50], aspen (*Populus tremuloides*) and Fremont's cottonwood (*Populus fremontii*) groves subjected to livestock grazing [51], and expansive thinning and burning that could reduce the integrity of MOG and riparian areas. This is especially the case if fire management removes too much biomass based on the tendency of forest managers to select an historical baseline of very frequent and low-intensity fires that then supports efforts to move forests too quickly into open stand conditions [43]. Fire return intervals and stand conditions may have been more varied historically, thereby supporting less aggressive approaches in MOG forests, Piñon–Juniper Woodlands, and riparian areas [6,46].

### *5.5. Conservation and Management Implications*

We provide a comprehensive ECA case study for mitigating and adapting to extreme climate conditions that will increasingly stress ecosystems and focal species in the MHE. Our approach integrates conservation and adaptation strategies for human and natural communities, which in this case is mainly about limiting wildfire ignitions spilling over into the built environment. With 24% of all fires intersecting the WUI over the period of analysis, we suggest that land managers focus treatments closest to homes and work with landowners to reduce the probability of home ignitions via home hardening and defensible space management [52]. Doing so would redirect vegetation management (e.g., thinning and burning) to nearest homes and focus on ecosystems that could benefit from the re-introduction of fire from wildland fire use (safely managing natural ignitions) and Native American cultural burning practices. Importantly, much of the controversy in fire risk reduction in the wildlands (backcountry) may be lessened by increasing the interval between burning and thinning prescriptions with the intent of leaving more of the understory intact, especially within MOG and riparian areas that may function instead as wildfire and climate refugia. For instance, some researchers [53] recommended at least doubling the time between agency fuel reduction treatments in the Southwest based on historical datasets showing more varied fire and forest density conditions to avoid type conversions affected by overly aggressive biomass removals and weed invasions that are apparent in many Southwest fuel reduction treatments [DellaSala, personal observations].

Our study also supports the importance of proposed Wilderness Areas and Wilderness Study Areas as well as a bump-up in the conservation status of IRAs (GAP 2.5) as connectivity maintenance for at least the two focal species and for cross-elevational linkages in montane life zones. Even so, with the addition of proposed protected areas (24.2% total), conservation targets would remain below the 30 $\times$ 30 protected area efforts [54], requiring additional conservation measures to contribute to overall state level and vegetation group targets. Any efforts to reintroduce grizzly bears need to be coordinated with the tribes, as much of the potential habitat is on their lands and could be accomplished via co-management agreements. The same is true for the maintenance of Mexican wolf connectivity, given much of the prime habitat is on tribal lands. Moreover, the incorporation of traditional Native American burning practices and traditional ecological knowledge can complement Western science, including access to proposed protected areas for traditional cultural, food resources, and spiritual values on proposed federal protected areas.

To reduce pressure on aspen and riparian areas, we recommend that land managers use livestock exclosures and fencing along streams and springs to keep livestock out of sensitive areas, longer periods of rest rotation to allow ecosystems time to recover, and efforts to mitigate the spread of invasive weeds by livestock [55]. Riparian restoration could also include reintroduction of beavers (*Castor canadensis*) to aid in water storage, stream channel morphology restoration (especially in livestock damaged stream beds), and the return of keystone functional relationships provided by this riparian obligate [56]. Doing so would also restore habitat for endangered riparian birds that occur in our study area and perhaps buy some time as stream flows likely decline due to loss of montane snowpack. Moreover, while not included in the analysis of our study area, springs and seeps are a recognized conservation priority in the Southwest that contain critically important isolated and refugia habitats for many species ranging from endemic plants and aquatic invertebrates to mollusks, herpetofauna, fish, and birds [57]. They provide water sources in wildlife corridors, serve as biodiversity hotspots, and would benefit greatly from some of the same conservation measures and restoration attention proposed.

## 6. Conclusions

The 11.3 M ha Mogollon Highlands Ecoregion is at the confluence of seven ecoregions, with taxa mixing from distant lands. Our study area is of central importance in maintaining connectivity for focal carnivores and plants and wildlife dispersing from climate-forced migrations. It is particularly important to maintain east–west connectivity along with elevation linkages in montane life zones to ameliorate some of the extreme effects of climate change and rewilding landscapes by closing and obliterating at least some roads. Road access reduction in turn would likely reduce unwanted anthropogenic fire ignitions that are often overlooked in fuel-centric management approaches [58]. We used a comprehensive ECA that integrated conservation needs of at-risk ecosystems and focal species with effective fire risk reduction designed to provide conservation groups and land managers with robust conservation planning in a radically changing climate. Rather than oppose forest and woodland protections, land managers could work with conservation groups, landowners, and tribes to integrate fire risk reduction with conservation priorities by focusing on proven defensible space and home hardening while increasing the interval between fuel-reduction treatments to allow ecosystems time to maintain and recover at least some native understories. Reintroduction of grizzly bears along with ongoing management of the Mexican wolf and the reintroduction of beavers in riparian areas in cooperation with interested tribes would help maintain the ecological integrity of the MHE along with protecting MOG forests for wildlife habitat, watershed maintenance, and carbon-storage benefits [6]. The Biden administration is currently considering nationwide MOG protections, and our study might inform this process by recommending the inclusion of older woodland (Piñon–Juniper) types in MOG conservation strategies.

Like many regions around the world, the MHE will continue to experience accelerating threats due to global overheating, even greater land use pressures, and demographic/population shifts. Thus, our approach will need to be periodically updated and monitored for efficacy in helping to solve conflicts over conservation and mitigate further losses. Our study also could be replicated in other portions of the Southwest, given that some of the same challenges arise around integrating conservation with adapting to wildfires, climate change, and fire risk reduction in the built environment. The ECA approach may also have application globally in showcasing how complex conservation challenges can be developed holistically and simultaneously to address human needs as well.

**Supplementary Materials:** The following supporting information can be downloaded at: https://databasin.org/galleries/5cd5cb2f98924985885415 74a94a2796 (accessed 20 November 2023): Figures S1–S8 and Tables S1 and S2.

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