Climate Change Effects on Central New Mexico's Land Use, Transportation System, and Key Natural Resources
Task 1.2

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Prepared by:
Ecosystem Management, Inc.
3737 Princeton NE, Ste. 150
Albuquerque, New Mexico 87107

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Introduction

The purpose of this report is to illustrate how planning decisions made today will affect central New Mexico's resilience to climate change impacts in 2040. This report first describes climate change impacts in central New Mexico. This report then describes actions that agencies responsible for land use planning and the provision, operation, and maintenance of transportation systems can pursue to increase climate change resilience. The resilience of transportation, land use, and key natural resources to climate change as well as climate change adaptation strategies are then described. This work is being done as part of the Interagency Transportation, Land Use, and Climate Change Scenario Planning Project in Central New Mexico.

Climate Change in Central New Mexico

The climate of the study area, central New Mexico (Figure 1), is highly variable as it is located on the boundary between the temperate mid-latitude zone and the subtropical dry zone, and the area's elevation ranges from approximately 5,000 feet to 10,600 feet. Climate change is projected to affect the atmospheric and oceanic processes that influence the location of the climate zone boundary and ocean-driven climate anomalies such as El Niño, La Niña, and the North American Monsoon (Llewellyn and Vaddey 2013).

The Bureau of Reclamation, Sandia National Laboratories, and the U.S. Army Corps of Engineers prepared the *West-Side Climate Risk Assessment: Upper Rio Grande Impact Assessment* report (Reclamation) which discusses future climate change (Llewellyn and Vaddey 2013). The projections of future change in temperature and precipitation were based on the National Oceanic and Atmospheric Administration analysis using the Coupled Model Intercomparison Project 3 (CMIP3) models and the North American Regional Climate Change Assessment Program models (Llewellyn and Vaddey 2013). The Upper Rio Grande basin-average mean-annual temperature is projected to increase by approximately 5° to 6° Fahrenheit (F) (during the 21st century; Llewellyn and Vaddey 2013). The *Climate Assessment of the Southwest* (CLIMAS) projects temperature to rise 1.3° F to 3.8°F during the 2021–2050 time period (Weiss 2013). The simulated annual climate averaged over the Rio Grande sub-basins is shown in Figure 2 (Llewellyn and Vaddey 2013).

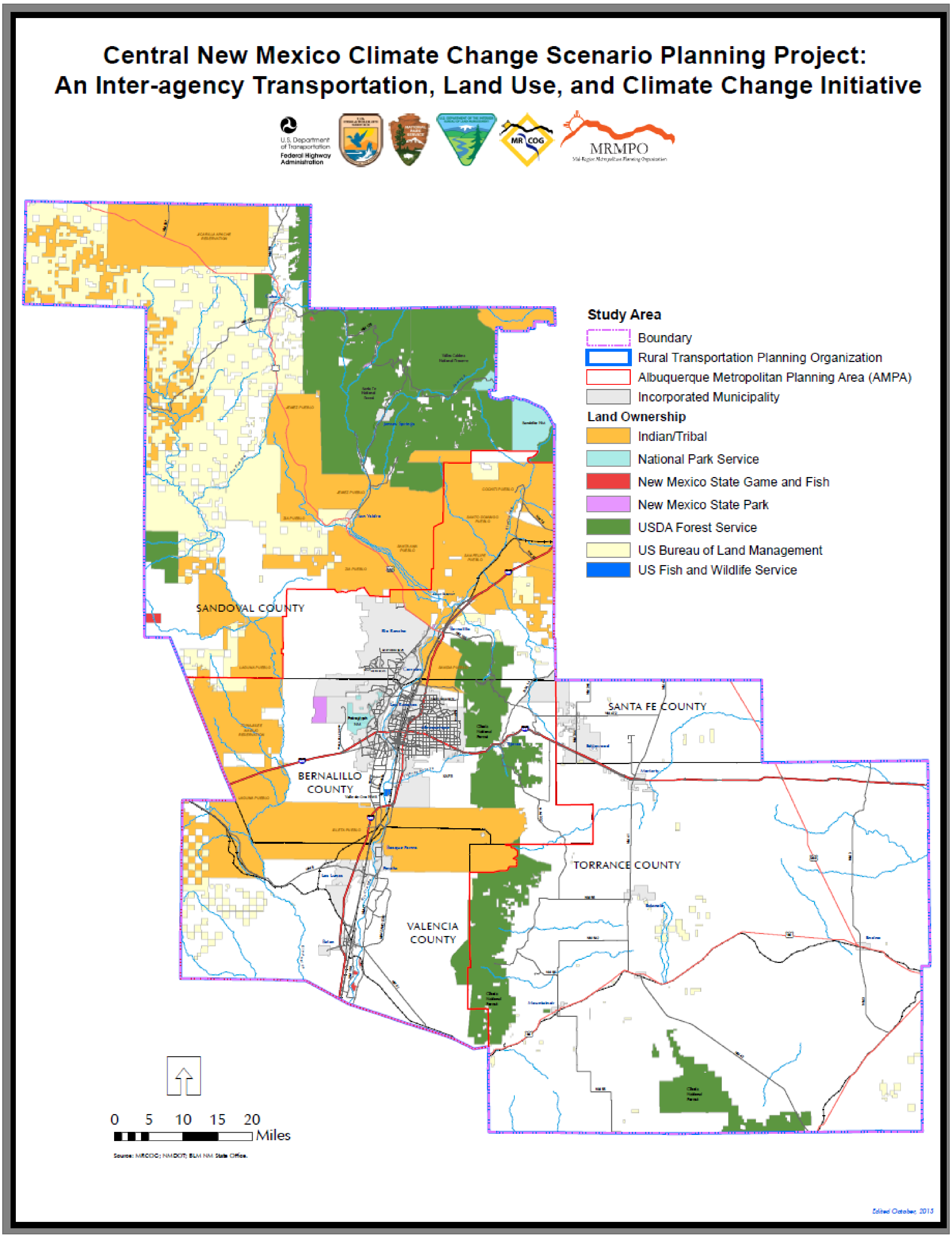

Figure 1. Central New Mexico Study Area.

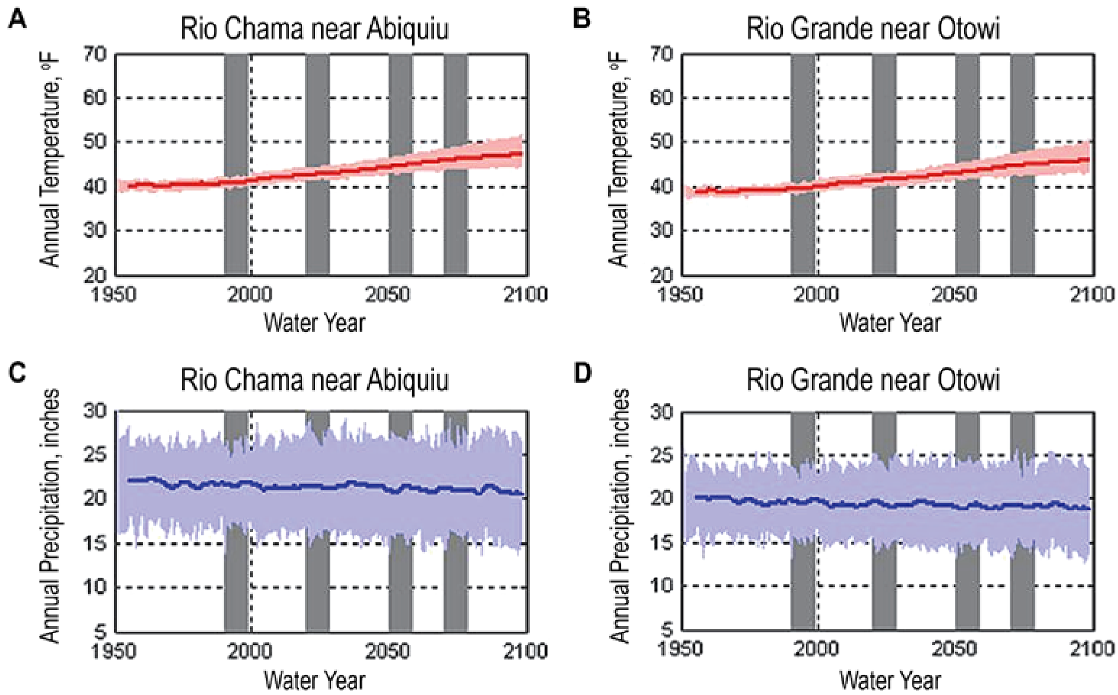

Figure 2. Simulated Annual Climate Averaged over Rio Grande Sub-Basins.

Both the Reclamation (Llewellyn and Vaddey 2013) and CLIMAS (Weiss 2014) reports state there is high confidence that the average temperatures will increase over the 21st century in the Southwest. Summer and fall temperatures will rise more than spring and winter temperatures. The number of cooling degree-days and the number of consecutive hot days will increase.

The Reclamation report cites model simulations for the Southwestern U.S. used in the most recent National Climate Assessment which projects changes in precipitation that range from -13% to +10%. The CLIMAS report concludes that annual precipitation in the Southwestern U.S. could change by -10% to +7% during the 2021–2050 time period.

Both the Reclamation and CLIMAS reports conclude that the predictions of precipitation levels have much greater uncertainty than for temperature. Precipitation may become more concentrated in a smaller number of more intense storms. More precipitation may fall as rain and less may fall as snow. The consensus is that temperature-driven increases in evaporation, regardless of whether precipitation increases or decreases, will lead to greater evapotranspiration, a net decrease in soil moisture, and a persistently negative water balance for the region (Llewellyn and Vaddey 2013).

Increased drought is likely in the Southwestern U.S. due to increased evaporation from higher temperatures regardless of whether overall precipitation increases or decreases, according to both the Reclamation and CLIMAS reports. Increased drought is likely to occur regardless of whether overall precipitation increases or decreases. Both reports identify three types of drought—meteorological, agricultural, and hydrological. Meteorological drought is a period with below normal precipitation. Agricultural drought is a period of dry soils, which could be caused by high temperatures due to evaporation, changes in land use, vegetative cover, or watershed hydrology.

Hydrological drought is declines in water storage and stream flow due to trends in precipitation, temperature, vegetation or land use.

Overview of the Land Use and Transportation Planning Process and Resiliency

Metropolitan planning organizations (MPOs) play important roles in the regional transportation and land use planning process. In central New Mexico, the MPO is the Mid-Region Council of Governments (MRCOG), which serves Bernalillo, Valencia, Torrance, and Sandoval counties and their constituent cities, towns, villages, and other governmental entities. Although local governments maintain ultimate land use authority, approximately every five years MPO staff integrate the visions of each member government into a long-range transportation plan that projects demographic, land use, and transportation conditions at least 20 years into the future. Additionally, every two years, the projects in the regional transportation plan are operationalized into a transportation improvement program that is updated biannually and lists particular projects that will receive funding over a six year period. Through the combination of plans and programs, MRCOG and other MPOs implement their long-term visions in a series of discrete investment decisions and policies. MRCOG is currently in the planning phase for *Futures 2040*, which is the update to its 2035 Metropolitan Transportation Plan.

The continuing, comprehensive, and cooperative nature of this process offers important opportunities to ensure that plans and programs are cognizant of and able to address emerging societal challenges, including consideration of climate change impacts, strategies for increasing resilience, and greenhouse gas reduction strategies. Indeed, the National Research Council recognizes that, "Decisions made today, particularly those related to the redesign and retrofitting of existing or the location and design of new transportation infrastructure, will affect how well the system adapts to climate change far into the future" (Committee on Climate Change and US Transportation 2008, p. 193).

The following two sections describe how land use planning and transportation investment decisions made today will affect central New Mexico's resilience to climate change impacts in 2040. In other words, although the impacts of climate change are already being felt in the region, sensible strategies can be assessed and adopted in central New Mexico that enhance the ability of the integrated transportation and land use system to better withstand additional climate impacts that are expected to occur in the future. These strategies may range from relocating infrastructure that is vulnerable to flood risks to deploying advanced pavement technologies that provide increased heat resistance and allow for water infiltration.

The concept of resilience has a long history in the study of ecological systems (see Holling 1973). There, it has been thought of as the capacity of a system to recover from unexpected changes, or the degree of an unexpected shock that would cause changes to the system (Adger 2000). For the purposes of this report, transportation and land use systems are considered resilient if they are able to absorb the impacts expected to occur from within a changing climate while still providing the fundamental services of mobility and accessibility. Similarly, if one element of the system—for example a link or a mode—fails, the overall system should still function at a relatively high level of service.

Transportation and Land Use Planning

Transportation and land use planning are inextricably linked. The location and design of transportation infrastructure within a region and the implementation of transportation policy affects the attractiveness of land for development (Giuliano 2004). Despite this interaction, transportation investment and policy decisions are typically made by different agencies than those that plan land use. Land use is controlled by city and county governments, whereas transportation planning is strongly affected by actions at the federal, state, and regional levels (Meyer 2006).This separation means that transportation and land use planning have not always occurred in concert; for example planned improvements to transit systems have not always been supported by increased development density and the full land use and travel demand implications of highway development have not always been considered during transportation planning. These issues cross municipal boundaries and require a regional perspective to navigate (Lewis and Sprague 1997, p. 9). MPOs typically address this need by considering transportation and land use planning at the regional scale. In central New Mexico, MRCOG fulfills this role and meets the requirements of federal law and regulations mandating the completion of fiscally constrained regional transportation planning.

The key point from the above discussion with respect to this report is that transportation investments interact with land uses and affect travel behavior. This realization constrains the range of realistic choices available to transportation and land use planners. When considering choices between land uses and development patterns (including density of residential and commercial development, zoning and the specific locations of various land uses, the provision of affordable housing, etc.) and a transit- or highway-focused transportation policy, not all combinations are desirable. For example, high-density residential and commercial development with a road focus would lead to serious congestion, and low-density development with a transit focus would likely be wasteful as transit vehicles could not be operated economically.

Below, the effects of land use and transportation infrastructure decisions are evaluated in terms of their likely effect on resilience. Although each discussion is presented separately, decisions made in one sector affect the other.

Effects of Land Uses, Growth Patterns, and Density on Resiliency

As discussed in the EMI report on Central New Mexico climate change impacts (herein referred to as EMI Impacts Report), the region can expect increasingly frequent heat waves, wildfires, drought, extreme precipitation events, and associated flooding (also see USDOI 2013, Weiss 2014). These findings are consistent with a 2004 report prepared for the New Mexico Floodplain Manager's association which stated that, "New Mexico's most significant natural hazards are flood, wildfire, drought and winter storms" (RCQuinn Consulting Inc. 2004, p. 3).

Below, land use decisions, policies, and strategies that can be employed in the short term to increase future resilience to these negative effects of climate change are described. The discussion addresses the resilience of the land use types outlined in the EMI Impacts Report, as applicable to each climate impact.

Heat Resilience and Urban Heat Island Effects

Increased heat exposure can lead to increased heat-related mortality, and these impacts are likely to be inequitably distributed across communities (McGeehin and Mirabelli 2001). The very young and the elderly are known to have a decreased ability to regulate body temperature (Kovats and Hajat 2008). Additionally, low-income residents of a city are less likely to have access to cooling and may have other complicating medical factors (Kovats and Hajat 2008). These patterns are likely to hold across different US cities (Uejio et al. 2011), although the impacts of the increment of additional heat are determined in relation to the starting temperature in a region (Pincetl et al. 2013). In other words, the difference between the heat wave temperature and the starting temperature is more closely linked to health outcomes than the absolute temperature.

Paved urban surfaces, buildings, and other materials located in a city store heat that is re-radiated throughout the day. As a result, core urban areas tend to be hotter than surrounding suburban and rural areas; this effect is known as the urban heat island effect. The effect is more pronounced in the nighttime hours, mediated by wind speed, cloud cover, and vegetation (Souch and Grimmond 2006). As a result of this effect, urban areas are likely to see increasing rates of heat-related morbidity and mortality under increasing temperature scenarios (McGeehin and Mirabelli 2001).

As noted by Hart and Sailor (2009), differences in urban forms are likely to have important effects on the urban heat island. These include:

> building density and building height to width ratio, roads and traffic density, building and surface materials whose thermal properties differ from the surrounding rural environment, the use of green space, and sky view factor [quantity of visible sky when viewed from the ground ranging from 0 to 1]. A city's canyon geometry [the layout of artificially created "canyons" resulting from the construction of tall buildings], building density and the materials used can absorb and store more incoming solar radiation due to a reduction in surface albedo or conversely store less energy due to shading. Canyon geometry causes the city surface to emit less long-wave radiation due to reduced sky-view factor. Urban surface characteristics can result in a reduction in evapotranspiration due to lack of vegetation and surface moisture. Urban areas are also sources of waste heat emissions due to anthropogenic activity (p. 398, citations omitted).

Very few studies have empirically investigated the relative importance of these effects in different locales. One exception is an empirical study of small-scale variation in urban heat island effects in Portland, Oregon which found that canopy cover was the single most important variable affecting urban temperatures in that city (Hart and Sailor 2009). Areas with more cover had lower temperatures. Industrial and commercial land uses were associated with higher temperatures, even exceeding temperatures in some areas of the downtown core. The authors hypothesized that shading due to high rise buildings reduces the uptake of solar radiation. Finally, some of the warmest areas in the city were above arterial road surfaces. This effect was more pronounced on weekdays than weekends due to vehicle-related heat emissions.

The net effects of any particular residential, commercial, or industrial development are not easily summarized and depend on site-specific considerations. In the Southwest, Phoenix has been extensively studied for urban heat island effects (Brazel et al. 2007, Uejio et al. 2011), due in part to its already high ambient temperatures and historically low-density land uses. Brazel et al. (2007) found that the urban core in Phoenix was approximately 2.2 degrees Celsius warmer than the rural countryside. Comparatively less attention has been paid to urban heat island effects in Albuquerque, or other central New Mexico cities. While findings in Phoenix may provide some indication of what is possible in cities in the Southwest, heat island effects in central New Mexico would likely differ somewhat from Phoenix because of the region's lower starting temperatures, differences in urban form, and the realization that most temperature increases in central New Mexico will be due to regional climate change effects as opposed to urbanization itself (Mishra and Lettenmaier 2011, Pincetl et al. 2013).

Efforts taken to mitigate urban heat islands can have an overall reductive effect on heat in cities. Land use decisions that consider not only density, but also building height, building materials, paved surface area, and vegetation could help improve the region's resilience to heat island effects. Different types of land cover can affect the severity of urban heat islands and overall temperature. Increasing vegetation can result in local cooling; white surfaces and roofs can be used to reflect, rather than absorb, heat; and less paved area overall can reduce the city-wide effects of the urban heat island. Green roofs, which involve planting vegetation on rooftops, can reduce the energy consumption of a building used for cooling by reducing its thermal gain (Saiz et al. 2006). Some work has also evaluated or hypothesized about the effect of green roofs on urban heat island mitigation. There is almost certainly a reduction in ambient temperature above the green roof (Wong et al. 2003), but the effects of implementing green roofs on a city-wide scale have yet to be tested. According to Saiz et al. (2006), studies in Toronto, Canada indicate that one third of the city area would experience a 1 degree Celsius drop in temperature with 50 percent penetration of green roofs.

In central New Mexico, planting additional vegetation requires additional water use, so implementing some forms of urban heat island mitigation could actually increase water consumption. White roofs and ground-level and green roof vegetation composed of drought tolerant plants (rather than high water use plants) are measures that mitigate effects of urban heat islands. When temperatures do climb, creating local cooling centers where people and families without access to cooling can go can also be an effective strategy for increasing the population-wide resilience to severe heat events by reducing the risk of death, especially for elderly residents.

These findings have implications for land use planning in central New Mexico. As development density increases, the same number of people and activities can be accommodated with fewer square feet of paved area. Reducing paved area reduces urban heat island effects, but the larger buildings that would be required to accommodate high-density housing in the urban core may have a countervailing effect, as their absorption of heat would be greater. At the same time, tall buildings may help maintain lower temperatures due to localized shading, depending on urban canyon geometry (Hart and Sailor 2009). The net effects of higher density development on urban heat are site- and design-specific. Locating new housing growth within the urban core would have the added benefit of making cooling centers easily accessible to large numbers of people. For any urban form developed, adding green space, canopy cover, and converting vacant lots into vegetated areas may also marginally reduce high temperatures.

Wildfire Resilience

In 2013, 221,951 acres (5% of all acreage burned in the US) burned in New Mexico (estimated from National Interagency Fire Center 2014). As the climate changes, the severity and frequency of wildfires is expected to increase in central New Mexico (USDOI 2013, Weiss 2014). Central New Mexico is already experiencing these types of effects; the region is currently in the midst of a very long stretch of unusually dry weather, and as recently as February 2014 there was an unusually early and severe wildfire on Isleta Pueblo (Brauer 2014, Ekwurzel 2014).

Wildfire Management in the Wildland-Urban Interface

Much of the high costs of wildfire arise from the settlement of people in close proximity to areas with high fire risk. The wildland-urban interface (WUI), or the area where human development transitions to undeveloped land, is the primary location of wildfire risk to human settlements (Hammer et al. 2009, National Association of Counties 2010). Ongoing demographic shifts across the US have put more people in close proximity to wildfire risk in the WUI over the past several decades as a result of low-density suburban development in the west and south (Hammer et al. 2009). According to the National Association of Counties (National Association of Counties 2010), "In the Western U.S. alone, the WUI increased in area by 61% during the 1990-2000 period and in total housing units by 68%...Current housing growth rates in the WUI have been nearly triple the rates of increase outside the WUI. Projections indicate 111% growth in the West and 93% growth in the Southeast are anticipated" (p. 2).

Figure 3 shows the extent of the WUI in relation to vegetated and non-vegetated development. See the EMI Impacts Report for discussion of the land uses currently located in the WUI in Central New Mexico. Figure 4 shows areas at higher risk for wildfire in the WUI. The wildfire risk model used to create Figure 4 was developed for the state of New Mexico Statewide Natural Resources Assessment, Strategy and Response Plan in 2010 as a collaborative effort between New Mexico Forestry Division, the New Mexico chapter of The Nature Conservancy, the Forest Guild, and stakeholders (The Nature Conservancy 2009; Nature Conservancy New Mexico Statewide Natural Resources Assessment). The wildfire risk layer was developed in 2010 by using three modeled fire behavior parameters (rate of spread, flame length, crown fire potential) and one modeled ecological health measure (fire regime condition class) with wildland urban interface areas and ignition probability. Fire behavior parameters were modeled using FlamMap, fire regime condition class was modeled using the FRCC tool, wildland urban interface areas were delineated using spatial data from the county level community wildfire protection plans within the state, and ignition probabilities were derived using fire history locations from 1987–2008. For a detailed description of each parameter, refer to the data atlas found at All about Watersheds information clearinghouse.

This data layer identifies areas with a relatively high risk of destructive wildfire. The intent of this map is to identify areas where forest management is most likely to reduce the risk of wildfire damage or to reduce the impact of wildfire on natural resources and human infrastructure and development. The most direct land use strategy that will increase wildfire resilience in central New Mexico involves reducing or eliminating housing, commercial, and industrial growth in the

WUI. Fewer residents and businesses in the WUI will lead to lower damages from any given event.

Other land use strategies and policies that can further increase resiliency to wildfire risk in the WUI include incorporating fire safety priorities into planning documents and deploying building and development codes that mandate fire mitigation measures (National Association of Counties 2010). These could include:

- "Defensible space": Requirements for buffer zones between development and wildland areas (see Figure 5 for an illustration of example distances). The National Wildland-Urban Interface Fire Program's Firewise Communities team recommends that Wildland-Urban Interface homeowners improve their "home ignition zone"-the house and surrounding area up to 200 feet (Firewise Communities). These requirements could include recommendations for "firescaping"—surrounding the building with vegetation that is less likely to combust.
- Deed restrictions or covenants placed on new developments that require the establishment of defensible space.
- Vegetation management plans: Site-specific analyses of vegetation and other features including schedules for fuel removal and cleanup.
- Special attention to fuel located downhill of houses sited on a slope.
- Requiring fire-resistant building materials for those structures built within the WUI.

Sample codes and ordinances are available online (National wildfire programs database).

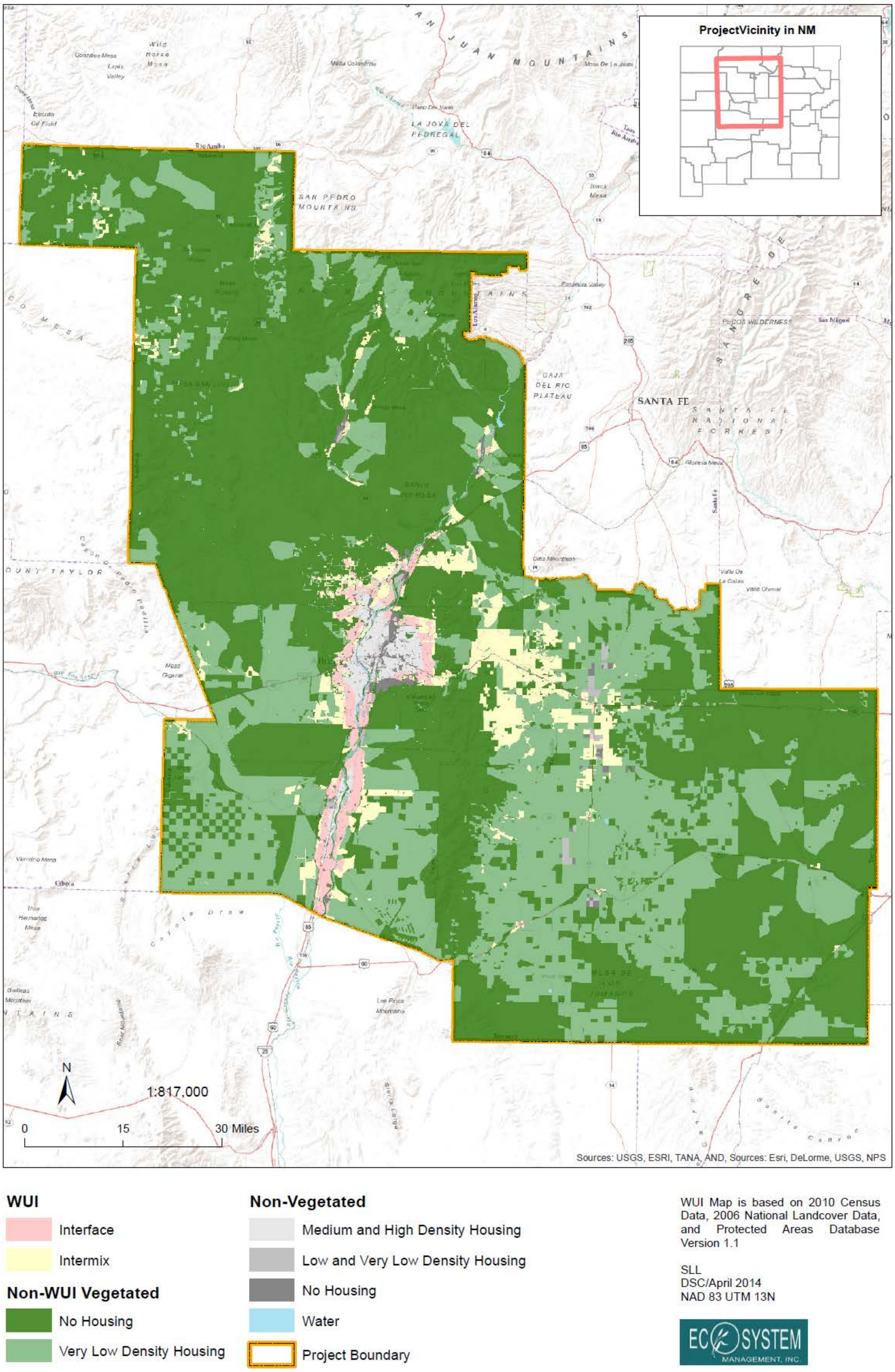

Figure 3. Wildland-Urban Interface Areas.

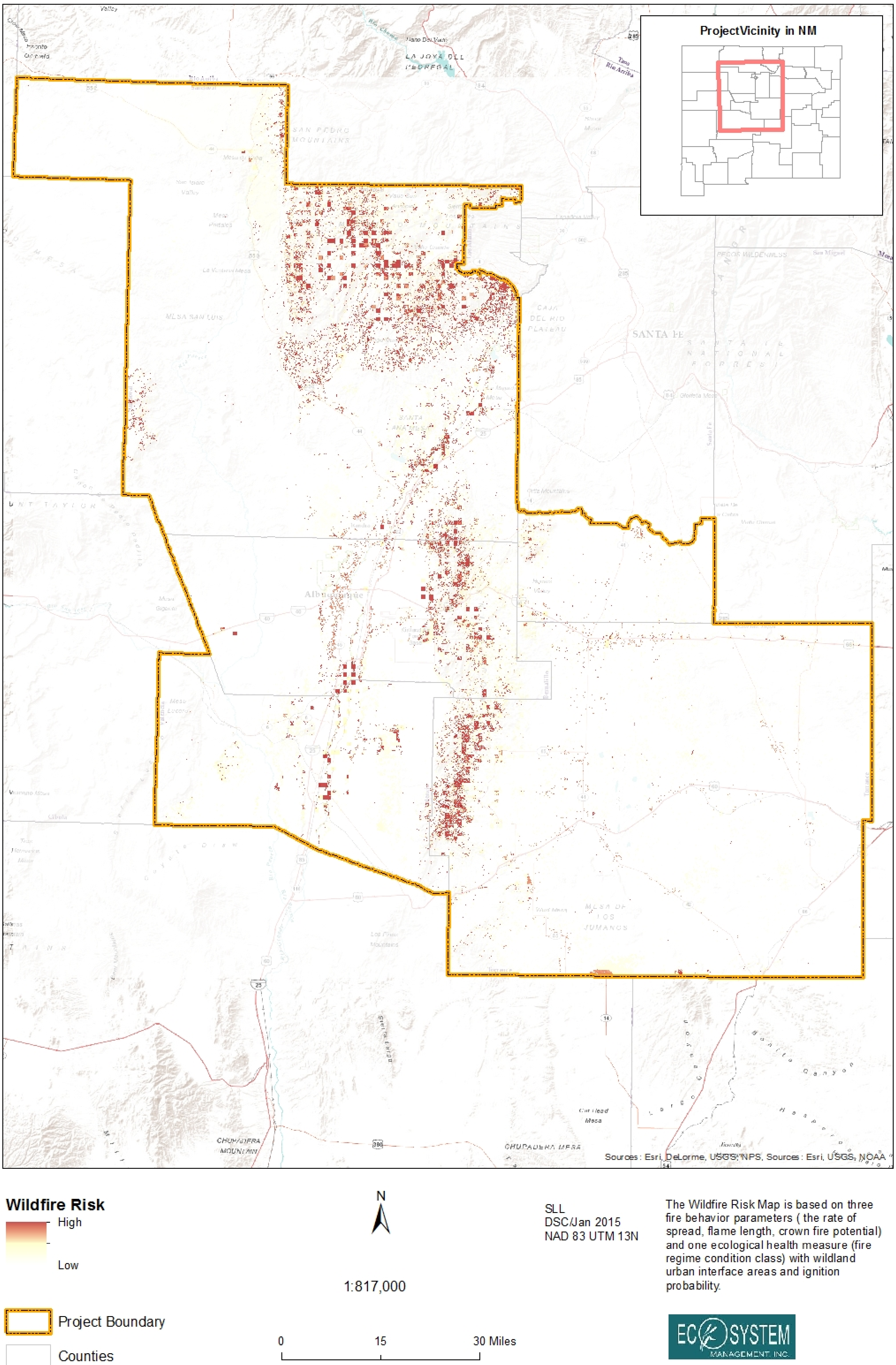

Figure 4. Wildfire Risk Map.

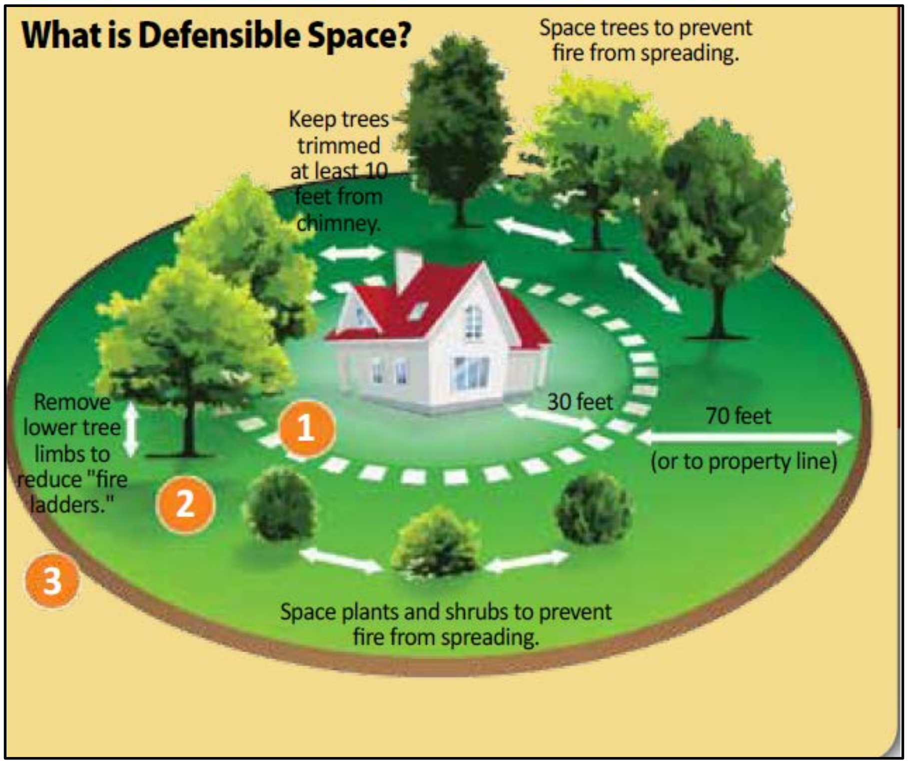

Figure 5. Example of defensible space requirements from Eagle County, CO. Source: (National Association of Counties 2010).

Since much of the WUI is located on the urban fringe, any development that occurs will likely be low-density. Such development will experience increased fire risk and more expensive fire suppression. If future development in Central New Mexico places homes or businesses in the WUI, the region will be less resilient to wildfires.

Open space and recreation lands, particularly those which are forested or have steep slopes, pose a wildfire threat to homes within the WUI. It has been suggested that "policies promoting a continuum of treatments with active management and reduction of fuel hazard in wildland-urban interface zones and reintroduction of fire in wildlands" will improve wildfire resiliency in these land uses (Dombeck et al. 2004).

Non-forested dry rangeland, while still susceptible to wildfires, does not support the very hot crown fires which spread rapidly from treetop to treetop, rather than on the surface, and cause very high levels of damage. Additionally, range animals help to reduce and control low-lying vegetation. Any residences or commercial or industrial land uses abutting dry rangeland in the WUI should still maintain defensible space to improve wildfire resilience. Irrigated agricultural lands typically have more green vegetation during "fire season" than either open space or rangeland, and would therefore pose less of a wildfire threat than either of the other two land use types.

In general, proper management of "non-developed" lands can help protect both residences and businesses in the vicinity and the lands themselves from wildfire. Fuel breaks are created in the WUI to reduce fire behavior and severity. Vegetation may be mechanically thinned, treated with herbicide, or prescribed burns may be set to create the fuel breaks. Shaded breaks, where the majority of vegetation is not cleared, can be less costly and serve as a conservation alternative to traditional fuel breaks. Community Wildfire Protection Plans have been prepared for the Middle Rio Grande, Santa Fe County, Bernalillo County, Sandoval County, and Torrance County. The narrow roads and acequias provide fuel breaks in the bosque.

In the WUI, there are a growing number of potential human sources of ignition, particularly with the development and improvement of roads, residences, and recreational opportunities into wildland areas. Human-caused fires increase the numbers of fire events that take place overall and increase the probability of fire occurrence throughout the year, including the winter months. This is particularly true in grassland and bosque ecosystems on state lands, as seen in the state fire records (Sandoval County 2008). Ignition sources for fires on the Forest Service Sandia Ranger District are about evenly split, with 48% human caused, and 52% lightning caused (Ciudad Soil and Water Conservation District and East Mountain Interagency Fire Protection Association 2006). Reducing the number of human-caused wildfires, whether by reducing the number of human interactions in wildland areas or educating the public on the importance of fire safety, would significantly reduce the risk of wildfire for land uses in the WUI.

Open Space Land Management for Wildfire Prevention

The state of New Mexico Forestry Division recognizes that restoring resiliency to landscapes will require strengthening its relationship to private and public sector organizations that specialize in components of ecosystem restoration beyond woodlands and forests and cross land jurisdictions (New Mexico Energy Minerals and Resource Forestry Division 2010). The New Mexico Forestry Division Wildland Urban Hazardous Fuels Treatment Program collaborated with the Claunch-Pinto Soil and Water Conservation District, the New Mexico Water Trust Board, State Parks, and the Natural Resources Conservation Service to treat properties in the Manzano Mountains southeast of Albuquerque. In two years, three large fires with extreme fire behavior destroyed homes and forests in areas where fuels were not thinned (New Mexico Energy Minerals and Resource Forestry Division 2010).

There are several methods that can increase resilience of vegetation to the risk of frequent and severe wildfires with climate change. Research finds that aggressive thinning for forest restoration can stimulate growth in large residual trees and improve drought resistance (Kerhoulas et al. 2013). Prescribed fire is a tool to sustain desired conditions for fire-adapted ecosystems and habitat for endangered species. Climate change may shorten winter seasons. Consequently, there could be a longer prescribed fire season for fuels treatments to reduce the risk of wildfires. Salvaging and converting biomass into boards and other wood products can help reduce carbon loss from fire, as a byproduct of forest restoration. Biomass that cannot be converted to wood products (such as from clearing roads and trails) can also be used for bioenergy production. Bioenergy production would be carbon neutral and could not only replace the use of fossil fuels in generators, but mobile generation facilities could also provide power to schools, hospitals, command centers, and other immediate needs (U. S. Department of Agriculture Forest Service 2010).

Wildfires and Water Quality

Wildfires can greatly increase runoff and erosion rates. The increase in erosion rates after high severity fires can be even greater than the increase in the size of peak flows because of the loss of soil aggregates and the exposure of the soil to rainsplash, sheetwash, and rill erosion. The net effect is that high-severity fires can increase sediment yields by two or more orders of magnitude. In many areas the risk of wildfires has increased as a result of human-induced changes in vegetation density, vegetation type, and the number of ignitions.

Over a millennial time scale, the amount of sediment delivered to streams from unpaved forest roads is equal to or greater than the amount of sediment that is delivered from high-severity wildfires. The chronic delivery of sediment from roads may be of greater significance to aquatic ecosystems than the pulsed delivery of sediment from high-severity wildfires, and forest managers should take steps to minimize road runoff and sediment delivery if downstream aquatic resources are being adversely affected (MacDonald and Larsen 2009). Extreme weather events due to climate change could increase the potential for severe erosion.

Post-fire rehabilitation treatments, such as seeding and mulching, are commonly applied to severely-burned areas to reduce post-fire runoff and erosion. These treatments can be very costly, especially for large wildfires. For example, $72 million was spent on postfire rehabilitation treatments after the 2000 Cerro Grande fire in New Mexico. The most common post-fire rehabilitation treatments are grass seeding, mulching, and the placement of contour-felled logs (Robichaud et al. 2000, Raftoyannis and Spanos 2005). Grass seeding has been the most widely used technique because it is relatively inexpensive and can be rapidly applied over large areas by aircraft. At the Cerro Grande Fire in New Mexico, the application of straw mulch plus grass seed reduced sediment yields by 70% in the first year after burning and 95% in the second year after burning (Dean 2001). Mulching also reduced sediment yields by an order of magnitude following the fire. Reforestation after wildfire may require different species than were present on the site pre-fire to better match site-type changes due to climate effects (U.S. Global Climate Change Program 2008)

Summary

As discussed in the EMI Impacts Report, climate change will threaten lives and increase costs across Central New Mexico. Based on the strategies discussed above and below in the key natural resources section, five general land use principles for increasing resilience to these impacts are:

1. Increased development density and centrality typically improves drought, heat island, and wildfire resiliency.
2. Reducing paved areas improves drought resiliency (by improving water supply), heat island effects, and flood resiliency.
3. Native landscaping can improve drought resiliency and wildlife connectivity.
4. Avoiding risky development locations in the WUI or in floodplains can improve wildfire and flood resilience.

5. Maintaining undeveloped space improves heat island resiliency, flood resiliency, and improves habitat connectivity, which is discussed in the following section. Proper management and design can improve wildfire, flood, and drought resiliency.

Table 1 provides a more detailed summary of the impacts on resiliency for each land use type described in the EMI Impacts Report. The table includes factors related to drought, heat, wildfire, and flood resilience sections (discussed above), as well as habitat resilience (which is discussed in the key natural resources section below). Note that parking and airports have been included in the Transportation section.

Table 1. Summary of climate resiliency characteristics and strategies by land use type.

Land Use	Summarized Climate Resiliency Characteristics and Strategies
Single-family residential (density < 8 / acre)	• Effects on heat resiliency differ by site. Green (vegetated) or white roofs and appropriate landscaping can mitigate the heat island effect and therefore increase heat resiliency. • Minimize new construction in the WUI to improve wildfire resiliency; if construction occurs, implement preventative measures. • Minimize new construction in high flood risk areas to improve flood resiliency. • Minimize overall paved area to improve infiltration and reduce flood risk. • Single family homes use more water per household and are less drought resilient (than multifamily residential). • Native landscaping and water mitigation measures can make these land uses more drought resilient and increase backyard habitat.
Multi-family residential (density > 8 / acre)	• Effects on heat resiliency differ by site. Green (vegetated) or white roofs and appropriate landscaping can mitigate the heat island effect, increasing heat resiliency. • Density with centrality improves wildfire resiliency. • Minimize new construction in the WUI to improve wildfire resiliency; if construction occurs, implement preventative measures. • Minimize new construction in the high flood risk areas to improve flood resiliency. • Minimize overall paved area to improve infiltration and reduce flood risk. • Multifamily homes use less water and are more drought resilient (than single family residential). • Native landscaping and water mitigation measures can make these land uses more drought resilient and increase backyard habitat.
Non-residential buildings:	• Effects on heat resiliency differ by site. Greater pavement area

Land Use	Summarized Climate Resiliency Characteristics and Strategies
Commercial Retail, Commercial Services, Commercial Major, Office, Office Major, Medical, Schools/Universities, Community, Mixed Use Industrial, Wholesale/Warehouse,	worsens the heat island effect. Green (vegetated) or white roofs and appropriate landscaping can mitigate the heat island effect. • Minimize new construction in the WUI to improve wildfire resiliency; if construction occurs, implement preventative measures. • Minimize new construction in high flood risk areas to improve flood resiliency. • Minimize overall paved area to improve infiltration and reduce flood risk. • Native landscaping and water mitigation measures can make these land uses more drought resilient and increase backyard habitat.
Agriculture–irrigated	• High water consumption will decrease drought resiliency. • Maintaining undeveloped irrigated agriculture mitigates the heat island effect and improves flood resiliency and habitat connectivity. • Crop choice and other mitigation measures can improve drought resiliency.
Rangeland–dry	• Maintaining undeveloped dry rangeland mitigates the heat island effect and improves flood resiliency and habitat connectivity. • Lower water consumption increases drought resiliency unless drought is severe enough that it leads to loss of economic productivity.
Open Space and Recreation (irrigated and dry)	• Maintaining undeveloped open space and recreation improves heat resiliency (by mitigating the heat island effect), flood resiliency, drought resiliency, and habitat connectivity.
Urban Vacant (vacant land–paved or not, abandoned structures)	• Increased pavement leads to decreased heat island resiliency. • Minimize overall paved area to improve infiltration and reduce flood risk. • Native landscaping makes these land uses more drought resistant and increases backyard habitat
Utility Rights of Way	• Placement of vegetated right of way can affect habitat connectivity and native landscaping can increase habitat.

Effects of transportation investments on resilience

Just as land use planning decisions can affect resiliency to climate impacts, so can the design and management of transportation infrastructure including roads, railways, bike/pedestrian facilities, waterways, and airports. This section describes general strategies for achieving resilience through transportation planning and design. The section then outlines more specific transportation planning strategies for increasing resilience to each expected impact of climate change. The resiliency of each transportation infrastructure category outlined in the EMI Impacts Report is discussed for each climate impact, as applicable.

General Strategies for Achieving Resilience through Transportation Planning

The National Research Council (NRC), the Federal Highway Administration (FHWA), and the Federal Transit Administration (FTA) provide helpful and similar typologies for approaches to minimizing the severity of future climate change impacts in the transportation sector (Committee on Climate Change and US Transportation 2008, Federal Transit Administration 2011, ICF International 2013). Although the FTA addresses transit assets in particular, there is some overlap with highway assets: both trains and buses traverse bridges and buses operate primarily on roads. Combining these three approaches and incorporating additional insights from related literature leads to seven general strategies for transportation agencies responsible for the provision, operation, and maintenance of infrastructure for developing resilient infrastructure systems in the face of climate change impacts:

1. Prepare for increased maintenance and repair costs while also incorporating preparedness for severe events into routine practices. Recognize existing institutional knowledge and expertise regarding extreme weather events, but acknowledge that these events will become more common in the future. Prioritize maintenance that reduces the risk of damage from extreme events such as clearing culverts of debris.
2. Collect data related to extreme weather events as well as past and potential future impacts and costs. Incorporate climate risks and the costs and benefits of making improvements into Transportation Asset Management programs, which can be used to prioritize investments, set goals and track performance.
3. Consider the effect of climate change on existing facilities 50 or more years into the future when planning for rehabilitation or retrofit. Design new infrastructure so that it is able to withstand the impacts expected in a warming climate (Liverman et al. 2013) and increase the safety margin for structures that have failed in the past. Consider "worst case scenarios" to identify critical infrastructure that may require more resilient design. Such designs may include increasing general drainage capacities, using heat-resistant materials, and including natural vegetation in design. Engineering design standards are also likely to require revision, but that process can take longer than the time available to adapt to changes already occurring (Meyer 2006).
4. Emerging technologies can be installed on new or existing infrastructure that can warn of dangerous climatic conditions (temperature, pressure, water level) that necessitate an immediate response. Develop and regularly update an emergency response plan, train staff for quick response, and develop a plan to communicate important information to the public.
5. Include redundancy in system design so that alternate service or routes are available in the event of a system disruption. Focus on the resiliency of the system rather than individual components of the system. This principle has important effects on the economic resiliency of a region (Meyer 2006).
6. Avoid placing transportation infrastructure in vulnerable locations. Remove assets from particularly vulnerable areas and site new ones in safer, less vulnerable locations (Liverman et al. 2013).

7. When planning transportation strategies for resilience, cross-agency collaboration must also be a key consideration. Some of climate change's impacts are expected to be so severe any individual agency's actions are likely to be insufficient to mitigate the worst effects. For this reason, agencies may be able to act as important examples that catalyze action at other levels of government and among private citizens and businesses. The sum total of these individual actions can result in a more resilient region overall.

Heat Resilience and Urban Heat Island Effects

There are expected to be important interactions between urban heat island effects and the provision of transportation infrastructure. At the same time, transportation infrastructure can be damaged by heat, although these damages can be minimized with appropriate action. Specific actions that transit agencies and agencies responsible for transportation infrastructure can undertake to reduce urban heat island effects and increase heat resilience are discussed below.

The construction of additional roads and parking lots within the Albuquerque urbanized area will increase the extent of the paved surface and worsen the urban heat island effect (Hart and Sailor 2009). Therefore, new construction should minimize road lengths and widths to improve heat resilience in the community. Planting vegetation alongside roadsides and parking lots, especially trees, creates more shade and helps to reduce the heat island effect (Hart and Sailor 2009). Transit-oriented transportation planning could help reduce the demand for parking lots as it generally results in decreased vehicle travel demand when implemented effectively (Ewing and Cervero 2010).

Paved surfaces including roads and parking lots are also vulnerable to damage as average temperatures increase (Committee on Climate Change and US Transportation 2008). Pavement- and bridge deck-embedded stress and strain sensors could be installed to monitor conditions under changing temperatures (Meyer 2006). New materials and better maintenance strategies can improve heat resilience of pavements (Committee on Climate Change and US Transportation 2008).

Bicycle and pedestrian facilities should be designed or retrofitted to include adequate shade and access to water along the route to improve user comfort and reduce the risk of heat-related illness. Because the pavement condition will suffer with temperature increases, increased pavement maintenance is important to improve the safety of the users of these facilities.

Rail buckling is a potential concern for the Rio Metro Transit District, Amtrak, and freight rail operators in central New Mexico. FTA recommends setting regionally-appropriate "rail-neutral" temperatures by either heating or pre-tensioning newly laid track (Federal Transit Administration 2011). The rail-neutral temperature is the temperature below which rail will not expand. Setting a high temperature allows for increased heat tolerance but also creates other failure risks during cold weather. An alternate strategy can involve the creation of expansion joints along rail that was previously continuously welded. To the extent that rail operators determine that particular areas of track (often those located in direct sunlight or around curves) are experiencing problems with buckling, railroad owners can create expansion joints in those areas.

For bus and rail transit operators, maintaining customer comfort and safety is of particular concern during heat events, especially when accessing the system involves outdoor waiting areas like bus or rail stops (Federal Transit Administration 2011). ABQ Ride, Rio Metro, and other regional transit operators should inventory the existing shade conditions at their bus stops and track customer complaints regarding heat to prioritize improvements. Building shade structures, planting trees near stops, or relocating stops to be close to existing tree cover would also increase the resiliency of the transit system to high heat and urban heat islands (Federal Transit Administration 2011). Using white roofs and installing energy-efficient air conditioning systems on transit vehicles can also improve rider comfort.

Employee safety is also important. Transit workers, transportation construction and maintenance workers, and contractors with an outdoor labor component should receive reduced work hours or be rescheduled during heat waves (Federal Transit Administration 2011, ICF International 2013). Using green or white roof principles in covered maintenance areas can reduce cooling loads and increase worker comfort (Federal Transit Administration 2011).

Wildfire Resilience

Transportation infrastructure located in the WUI is at a greater risk of being damaged by wildfire. The most sensible transportation strategy for increasing wildfire resilience would be to not locate transportation infrastructure in the WUI zone beyond what is needed to provide mobility and evacuation needs for existing WUI residents. At the same time, roads and their rights-of-way can be used as additional defensive space to separate homes from wilderness, increasing the homes' resiliency to wildfire (Brzuszek et al. 2010). Proper signage and multiple wide, well-maintained ingress and egress points for a development for both evacuation and emergency services purposes can improve wildfire resiliency for both individual homes and the community as a whole (DeGomez 2011).

Drought Resilience and Water Supply/Consumption

Transportation infrastructure can affect drought resilience and maintenance of water supply through its stormwater runoff effects. Paved roads and parking lots prevent water from percolating to the groundwater table and create runoff with poor water quality. These problems can be mitigated by reducing the area of pavement or using a permeable pavement which can reduce runoff, recharge groundwater, and prevent pollutant contamination (Scholz and Grabowiecki 2007). Even when a permeable pavement is not suitable for a particular roadway, it can be still be used for road shoulders and bicycle and pedestrian infrastructure. Parking lots, driveways, and fire roads are among the other potential uses of permeable pavement (Scholz and Grabowiecki 2007).

Other solutions include shifting right-of-way plantings to drought resistant species and designing both infrastructure and road right of ways to slow runoff (Meyer and Weigel 2011) and allow it to soak into the ground. Where feasible, lining channels with natural materials such as gravel rather than concrete and designing culverts and other infrastructure to slow water runoff speeds can help improve water percolation, groundwater recharge, and water quality.

Flood Resilience

Floods can impact all types of transportation infrastructure: roads, rail, waterways, and airports. Locating (or relocating) transportation infrastructure outside of or above high flood-risk areas (as feasible) can reduce damages to transportation infrastructure. This strategy may be particularly important for facilities that are crucial for evacuation, safety, or economic purposes.

Several transportation practices can reduce the potential for localized flooding, reducing damages to both transportation infrastructure and other facilities in a community (buildings, vehicles, etc.). These include "rain gardens, stormwater ponds, trees, native plans, pervious pavements, and native vegetation buffers along roadways" (Federal Transit Administration 2011). Additionally green roofs and rainwater harvesting can reduce flood flows. As discussed in the drought and water supply section above, reducing the amount of pavement and using pervious pavements can help reduce the overall amount of runoff, and thus the amount of water available to create a flooding event. In creating a modeling tool for planners, Harbor noted that "in a sample analysis, conversion of woodland to high-density residential and commercial uses causes an eleven- to nineteen-fold increase in runoff volumes, and loss of 11 to 100 percent of the natural groundwater recharge" (Harbor 1994). Roads and transportation infrastructure make up a significant portion of impervious surfaces in residential and commercial land development, and minimizing their footprint is key to reducing stormwater runoff. A study of driveway pavements found that using permeable pavers increased infiltration rates to an average of 11.2 cm/hr over the negligible rate of asphalt and reduced stormwater runoff as compared to asphalt driveways as well (Gilbert and Clausen 2006).

Although stormwater mitigation practices enacted at the level of an individual transportation agency are likely to have a relatively minor effect on overall (rather than localized) flood flows, these organizations can demonstrate leadership on enhanced stormwater management and encourage other public agencies and private individuals to take action. In combination with direct mitigation of stormwater volumes, bus transit operators such as ABQ Ride and Rio Metro should consider the location of their bus storage facilities in relation to areas of increased flood risk (e.g., the Rio Grande floodplain and other areas of elevated flood risk). Because unexpectedly high volumes of water can inundate these areas rather quickly, maintaining awareness of expected flood conditions and having contingency plans in place for vehicle relocation can protect rolling stock. Although more difficult to protect in the event of a flood and difficult to relocate, the location of administrative offices should also be considered.

Roads in flood-prone areas should be designed with increased slope and modified subgrades to facilitate water removal and improve the safety and longevity of the road. Design standards, including at the transportation agency level, should be updated to accommodate changing environmental conditions (Meyer and Weigel 2011). Increases in intense precipitation events will also necessitate updating design specifications for culverts and stormwater systems to provide for greater capacity and shorter recurrence intervals (Committee on Climate Change and US Transportation 2008). Culverts constructed at least 1.2 times the bankfull width allows for the unrestricted movement of fish and wildlife. Greater mobility for fish and wildlife will enable them to respond to rising temperatures as the climate changes.

Bridge assets are also at particular risk under increasingly severe climate scenarios due to "bridge scour" where high velocity flows can remove soil at bridge piers resulting in weakened supports. Bridge scour is a mitigation issue for existing structures and a design issue for future ones. Expected future levels of the Rio Grande should be analyzed and incorporated into the design of new structures. Deng and Cai (2010) describe two broad categories of scour mitigation: armoring and flow alteration. Armoring adds an additional layer of protection to the pier to resist hydraulic shear stress and protect the underlying materials from erosion. Flow altering techniques change flow properties in an effort to directly reduce scour. The most common armoring technique involves riprap and flow-altering measures include submerged vanes, sacrificial sill, collars and slots, parallel wall, and others (Deng and Cai 2010).

Culverts are at risk of being washed out, exceeding capacity, or being plugged by debris and vegetation during large storm events, resulting in localized flooding. According to the New Mexico Floodplain Managers Association, "many bridges and culverts are not designed to carry the 100-year frequency flood flows, which causes raised water levels upstream whenever their capacities are exceeded. Overflow of channels and flooding results" (New Mexico Floodplain Managers Association 2003). Such under-design has resulted in flooding events in the past, indicating that in the future even larger culvert designs may be needed to accommodate the larger storm events predicted to result from climate change. Neighboring Arizona has also listed increasing culvert capacity and ensuring existing culverts are sufficient to deal with flooding as responses to climate change in its *Preliminary Study of Climate Adaptation for the Statewide Transportation System* (Tao and Leary 2013).

Summary

There are several general principles, which agencies responsible for the provision, operation, and maintenance of transportation infrastructure can follow to increase future climate resilience. These principles include considering future conditions when decisions are being made about repair, replacement, or retrofit; preparing for increasing maintenance and operations expenses; preparing for currently "extreme" events to become more frequent; building redundancy into the system; locating new facilities away from vulnerable areas; and moving existing assets out of those areas where possible.

It is not possible to generalize the effects of a specific infrastructure type on climate resilience, since the effect depends on design, location, supporting land use, and use. For example, a heavily used rail line located in a floodplain would decrease system resilience while the same line located to connect high-density residential and employment locations might increase resilience by providing a convenient alternative evacuation route. To the extent that new transportation infrastructure is planned to facilitate more resilient land uses, the effects of that infrastructure on resilience are likely to be positive (see the discussion above in the "Transportation and Land Use Planning" section). However, there are infrastructure-specific technologies and measures that can be employed to increase resilience of transportation infrastructure itself. These are summarized in Table 2. The table includes factors related to drought, wildfire, heat, and flood resilience sections (discussed above), and habitat resilience (discussed in the key natural resources section below).

Table 2. Transportation strategies to increase the region's resilience.

Transportation Infrastructure	Strategies to increase the region's resilience
Road pavement	• Embed sensors to warn of changing conditions • Use permeable pavements to mitigate flood flows • Reduce paved areas in general • Improve materials and road maintenance strategies to reduce heat impacts • Design road slopes and subgrades to accommodate flooding events
Roadway elements (signage, signals, lighting, guard rail, barriers, etc.)	• Use effective signage to facilitate wildfire and flood evacuation • Minimize street lighting in rural areas to reduce impact on animal habitat
Bike/pedestrian facilities	• Use permeable pavements to mitigate flood flows • Provide adequate shade and access to water • Improve path materials and maintenance strategies to reduce heat impacts
Bus transit	• Provide shaded areas for customers • Cool buses and shelters
Rail lines and related infrastructure	• Use a regionally-appropriate (and high) "rail-neutral" temperature for new track • Provide shaded areas for customers • Cool train cars
Parking lots and airports	• Use permeable pavements where appropriate to mitigate flood flows • Reduce paved areas in general • Improve materials and pavement maintenance strategies to reduce heat impacts
Bridges, major structures, and culverts	• Embed smart sensors to warn of changing conditions • Bridge scour mitigation strategies • Increase designed capacities
Storm drain systems and flood control infrastructure	• Improve drought resiliency and water supply through system-wide mitigation strategies • Stormwater retention, detention, and increased infiltration • Update design standards to improve flood resiliency
Landscaping and roadside vegetation	• Roadside vegetation, especially native landscaping, improves habitat and habitat connectivity and can improve transit customer comfort • Right-of-way designs can slow stormwater runoff and allow infiltration

Key Natural Resources

Resilience of natural resources to climate change is the capability of the resource or natural system to respond to and recover from significant multi-hazard threats with minimum damage to the resource. Resilience improves the capacity of the resource to return to prior conditions after disturbance. Adaptation is an adjustment in the natural system to new or changing environment that exploits beneficial opportunities or moderates negative effects (Natural Resource Council 2010). Preserving natural habitat is an important part of ecological resiliency to both urbanization and climate change. Climate change is poised to impact a number of ecological communities and species in New Mexico, especially those which have already been affected by historic development of the Upper Rio Grande (EMI Impacts Report). This section discusses the resilience of the Rio Grande, habitat connectivity, vegetation, and threatened and endangered species as well as policies to increase the resilience of natural resources in general. A summary of climate change adaptation strategies is provided in Table 4.

The Rio Grande

The Rio Grande is a key natural resource in central New Mexico as it provides a water supply for drinking and agriculture, habitat for endangered species, riparian vegetation, recreation, and open space. Several programs have been developed to protect and restore the natural resources in the middle Rio Grande. These programs will contribute to the resiliency of natural resources to climate change impacts.

The U.S. Department of Interior established a committee to prepare *A Citizens Report: A Secretary's Committee for the Middle Rio Grande Conservation Initiative* (2012). The report states that for the Rio Grande to endure as a resilient system to climate change effects, partnerships among local, state, federal and tribal entities and numerous public and private organizations are essential to meet the challenges of climate change, in particularly water shortages. The report emphasizes that conservation of the Middle Rio Grande requires an ecosystem approach along the entire stretch of river; restoration of hydrological, biological and geomorphological processes; and landscape level connections between private lands and publicly-owned protected areas. Key plans for this effort include the Bosque Biological Plan, the Rio Grande Valley State Park Management Plan, the Middle Rio Grande Ecosystem Restoration Project, the Middle Grande Water Bird Plan, the Middle Rio Grande Endangered Species Collaborative Program, and the Save Our Bosque Task Force. Several of these projects and plans, described below, will increase the resilience of riparian vegetation, threatened and endangered species, and crucial habitat to climate change through providing water for ecosystem services and increasing habitat connectivity.

The Bosque Biological Plan lists several recommendations for conservation of the Middle Rio Grande (Crawford et al. 1993, Robert 2005). This plan is currently utilized by many agencies as they develop their own projects and plans.

- Coordinate Rio Grande water management activities to support and improve the bosque's riverine and terrestrial habitats, with special emphasis on mimicking typical natural hydrographs.

- Implement measures to allow fluvial processes to occur within the river channel and the adjacent bosque to the extent possible.
- Reintroduce the dynamics of surface-water/ground-water exchange, manage ground-water withdrawal, and restrict contamination.
- Protect, extend, and enhance the structure of aquatic habitat to the benefit of native communities.
- Protect and enhance surface-water quality.
- Integrate management of nonnative and native fish species in all aquatic environments in the Middle Rio Grande riparian ecosystem including wetlands, canals, and drains.
- Protect the geographic extent of the Rio Grande bosque and avoid further fragmentation of the riparian ecosystem and component habitats.
- Protect, extend, and enhance riparian vegetation in noncontiguous areas in the floodplain.
- Manage the buffer zone of the contiguous bosque to protect ecosystem processes, enhance wildlife habitat values, and maintain rural and semirural conditions.
- Manage livestock grazing in a manner compatible with biological quality and ecosystem integrity.
- Manage activities that remove dead wood in a manner compatible with biological quality and ecosystem integrity.
- Manage recreational activities in the bosque in a manner compatible with biological quality and ecosystem integrity.
- Prevent unmanaged fires in all reaches of the bosque.
- Use native plant species and local genetic stock in vegetation establishment and management efforts throughout the bosque.
- Protect, enhance, and extend (create) wetlands throughout the Middle Rio Grande riparian zone.
- Sustain and enhance existing cottonwood communities, and create new native cottonwood communities wherever possible throughout the Middle Rio Grande riparian zone.
- Contain the expansion of existing large stands of nonnative vegetation in the Middle Rio Grande riparian zone. At the same time, study the ecology of these stands and develop creative ways of maximizing their biological values.
- Develop a coordinated program to monitor biological quality (with emphasis on the diversity and abundance of native species) and ecosystem integrity (with emphasis on restoring the functional connection between the river and riparian zone) of the Middle Rio Grande ecosystem.
- Develop a coordinated research program to study the ecological processes and biotic communities that characterize the Middle Rio Grande riparian ecosystem.
- Regularly review and update the Middle Rio Grande Ecosystem: Bosque Biological Management Plan.
- Integrate resource management activities along the Rio Grande and within the contributing watersheds to protect and enhance biological quality and ecosystem integrity.
- Develop outreach initiatives through public education programs and events, and community participation activities and projects, to broaden public understanding of and

generate more active interest in bosque restoration and river ecosystem management in the Middle Rio Grande.

The Middle Rio Grande Restoration project was developed by the U.S. Army Corps of Engineers in response to the U.S. Fish and Wildlife Service's Biological Opinion to create and restore habitat for the endangered Rio Grande silvery minnow and the Southwestern Willow Flycatcher. The project will restore 916 acres of native riparian cottonwood forest between the Isleta Pueblo and the northern border of the Sandia Pueblo.

The Middle Rio Grande Endangered Species Collaborative Program (MRGESCP) involves 16 signatories to improve and protect the habitat for endangered species in the Middle Rio Grande, particularly the Rio Grande Silvery Minnow and the Southwestern Willow Flycatcher. The MRGESCP restores habitat, monitors endangered species, propagates the Rio Grande silvery minnow, and acquires and manages water. Refugia for the silvery minnow have been established.

The U.S. Army Corps of Engineers applied a community based index model for the bosque (riparian) ecosystem using standard Habitat Evaluation Procedures (HEP) for restoration along the Middle Rio Grande (U.S. Army Corps of Engineers 2012). The proposed restoration activities are shown in Table 3.

Table 3. Proposed features and activities for ecosystem restoration efforts in Middle Rio Grande

Category	Features/Activities	Details
Hydrology and Hydraulics	Wetland Restoration	Wetlands would be established or restored at appropriate locations to create a diverse and high value habitat. Storm water outfalls were numerous throughout the bosque in the Albuquerque area and would be modified to function as wetlands, increasing diversity of habitat and providing some water quality treatment. There was an existing oxbow wetland that would also be restored to function more naturally. Restoration of wetland habitat was critical to ensuring that the dynamic mosaic of the bosque ecosystem's structure and function was perpetuated.
	Channel Modification	In several areas, banks of the Middle Rio Grande would be shaved to create a less incised channel and shelves, or destabilized to create sediment sources. Such areas would increase the diversity of both fringe riparian and aquatic habitat.
	High Flow Channels	Excavation of smaller, high flow channels to convey waters through the bosque during typical spring flows would occur. This would mimic the historic hydrograph and recreate connections between the bosque and the Middle Rio Grande.
	Swales	A number of areas had also been identified for installation of moist soil willow swales that would serve a dual purpose of reestablishing connectivity between the bosque and the river, as well as providing shrub, mid-canopy habitat—an integral piece of the bosque ecosystem mosaic.
Vegetative	Cottonwood Riparian Gallery Forest	A primary element of the restoration would be the planting and reestablishment of cottonwood/willow gallery forest communities within the bosque. Areas would be cleared of exotic species and

Category	Features/Activities	Details
	Communities Restoration	replanted with native species of cottonwood riparian gallery forest. Especially important would be the reestablishment of the mid-canopy vegetation and open grasslands/savannahs to ensure that the dynamic mosaic of the bosque ecosystem was restored.
	Exotic Species Removal	A key element in the restoration of the bosque focuses on the removal of exotic plant species. Salt cedar, Siberian elm, tree of heaven and Russian olive were foreign exotic species that invaded parts of the bosque, forcing out key native species of willow and cottonwood. In addition, removal of exotics would potentially allow the water table to return to higher levels in this area of the Middle Rio Grande bosque because many of these exotic species use more water than native species. Removal of exotics would improve the potential to reestablish native species over the long term. Exotic removal was considered a precondition for the restoration of natural processes in the bosque. Removal of exotics would also help decrease fuel loads because they comprise most of the understory in denser areas of the bosque.
	Fuel Load Reduction for Wildfire Resilience	Another key element to enhancing the health of the bosque would be fuel load reduction. Fuel load reduction entailed removing dead and down wood and excess leaf litter within the cottonwood gallery forest. When the flood disturbance regime was still functional, much of this material would have been removed by periodic flooding. Much of this material represented a fire hazard, and in many instances encroached on recreation systems and limited the surveillance necessary for security within the bosque. Fuel load removal would advance a number of objectives of the study.
Physical Removal	Jetty Jack Removal	Another important measure proposed in alternative development was the removal of jetty jacks. Jetty jacks were originally used to stabilize banks and control floods within the Middle Rio Grande floodplain. Jetty jacks would be removed wherever possible and left only where they were critical to levee stabilization.
	Debris Removal	Fires and extreme storm events will increase debris. Debris and fill foreign to the floodway system would be removed to create a suitable restoration substrate. Debris would be completely removed except where it was part of an existing levee.

Transportation Infrastructure and Natural Resource Resilience

The construction and operation of different types of transportation infrastructure is likely to have important effects on the resiliency of local ecosystems to climate change. In 1998, an estimated 15 to 20 percent of the U.S. land area was directly affected ecologically by roads (Forman and Alexander 1998). The percentage of land that is affected by roads has likely increased since this time. The field of road ecology has emerged over the last decade to describe the direct ecological impacts of roads on habitat connectivity and wildlife populations and to prescribe mitigating designs (Forman et al. 2003).

Roads can act as barriers which hinder the movement of animals and fragment breeding populations (Coffin 2007). Roads that cut through traditional migration, breeding, or hunting grounds can pose a significant problem for some species. Animal collisions with vehicles often result in wildlife death, either on impact or later because of an animal's inability to feed itself due to injuries sustained. Wider roads impose more of a barrier; by building narrower roads, animals are allowed a better opportunity to cross, though they are still exposed to vehicles. Additionally, there is an increased risk of unanticipated wildlife migrations on the transportation system due to climate change impacts on habitats for species. To address these impacts, transportation agencies should identify wildlife migration on roads, review road kill and crash data, and design for supportive wildlife crossing areas. Planning habitat corridors and aligning new road networks with corridor goals can help reduce habitat fragmentation and prevent animal-vehicle collisions. Roadside vegetation can also provide wildlife corridors and connectivity in more developed regions. Some species even choose to live in these buffers when they are properly managed (Coffin 2007). Other mitigation efforts for roadways include creating wildlife crossings, and even wildlife overpasses, often in conjunction with high fencing, narrower roadways, and conscientious route design, among other solutions (Forman 2010).

Transportation infrastructure can also create noise or microclimate problems in the immediate vicinity such as increased dust, heat, or wind (Coffin 2007). Artificial night lighting, including headlights and streetlights, can also confuse animals and have significant ecological impacts such as disrupting migration patterns and altering reproductive behaviors (Longcore and Rich 2004). Planting native vegetation in road right of ways or installing barriers in some areas can help to mitigate some of these effects. Using quieter pavements can mitigate noise impacts (Forman 2010). Reducing street lighting in non-urban areas to the minimum required for safety could reduce disorientation caused by lighting.

Stormwater runoff from roads adversely impacts ecosystems and wildlife. Paved surfaces disrupt natural water flows causing higher and more damaging peak flows. During dry periods, paved surfaces may also disrupt lower base flows, which would otherwise seep into the groundwater. These effects are exacerbated during extreme precipitation events, which will likely become more frequent as a result of climate change. Pollutants from stormwater also harm fish and wildlife and degrade aquatic habitat. Poorly designed stream crossings hinder aquatic organism passage. Culverts may be too shallow or are placed above the streambed. If they are too small, streamflow is restricted during extreme events causing erosion, blockages, and floods.

In the summer, people seek recreation in the cooler elevations or near water in central New Mexico. Higher temperatures due to climate change will increase use of the facilities and roads in those areas including the Cibola National Forest. Effects of roads and traffic on plants and animals include the loss and fragmentation of habitat; loss of connectivity for species; increased rates of wildlife mortality because of collision with vehicles; alterations to light, moisture, and wind regimes due to the creation of edges; pollution from traffic (e.g., light, noise, and chemical); and facilitating the spread and dispersal of weeds and feral animals. Road avoidance, especially due to traffic noise, has a greater ecological impact (Di Giulio and Holderegger 2009). Vegetation adjacent to roads often provides habitat (Bissonette and Rosa 2009), and in some landscapes, even the majority of habitat (van der Ree and Bennett 2003). The density of roads and trails has contributed to habitat fragmentation and wildlife disturbance, especially in the

Cedro area in the Manzanita Mountains south of Interstate 40 (U.S. Department of Agriculture Forest Service 2008). Fragmentation may increase the difficulty for species and habitats to migrate as climate changes. As more roads are constructed and traveled, more impacts will be incurred by key natural resources that will be less resilient due to climate change.

Tijeras Canyon Case Study

Tijeras Canyon, east of Albuquerque, provides an example of an area in central New Mexico where transportation infrastructure has been designed to minimize impacts on wildlife and habitat. The area has been identified by the New Mexico Game and Fish Department and several national environmental groups as the most critical wildlife crossing area in New Mexico. Mule deer, black bear, and other wildlife migrating between the Sandia and Manzanita Mountains have been hit by vehicles on a regular basis. On the Interstate 40 project in Tijeras Canyon, eight miles of deer fencing were installed and five wildlife underpasses enhanced. Elements of this project include the fencing of the Interstate, which alone would have created a major reduction in animal/vehicle collisions but would not have assisted animals with the need to cross the highway. To accomplish permeability, an existing multiple-chambered culvert and underpass were modified to be more wildlife-friendly. A bridge that was so heavily vegetated that it reduced visibility through the structure beyond what was appealing to many species of wildlife was cleared to a reduced level. The project was at the location of exit/entrance ramps, so a system was necessary to reduce the possibility than animals would enter the interstate through these ramps. The state installed a system called Electromat, which is an embedded electrical system that causes an aversive but not dangerous shock. An Animal Detection System was also installed to warn drivers of animals crossing in areas that could not be fenced.

Land Use Planning and Habitat Connectivity Resilience

It is not simply the size and location of natural habitat that is important for ecosystem function, but also connectivity. Suitable habitat often remains unused if isolated (Hanski and Thomas 1994). Land use plans can improve habitat resilience by designing for habitat connectivity. To maintain wildlife corridors, establishing contiguous parkland through which animals can pass is essential. Parks, greenbelts, and natural stream channels are some of the more readily apparent urban and suburban contributors to habitat area and connectivity.

Connectivity can also be improved by enhancing the matrix of vegetation in backyard habitat, planted boulevards, and utility rights of way within developed areas (Rudd et al. 2002). Open space and vacant land, preferably left in a "natural" state, adds to these habitat areas. Even paved areas and abandoned buildings, however, can provide habitat and shelter for native species, and in time can revert to a more natural state. The use of native plants in landscaping, whether public or private, or residential or commercial, can improve upon a network of parks, greenbelts, and open space. Where development is densest, special care should be taken in designing open spaces that allow for the movement of animals to nearby habitat.

Animals and insects are not the only beneficiaries of habitat corridors and networks. Plants also increase in biodiversity, both within and outside of designated habitat areas. Species richness of animal-dispersed plants increases in response to the connectivity provided by corridors, while the higher edge-to-interior ratio of greenbelts and corridors increases the species richness of wind-dispersed plants outside of designated habitat space (Brudviga et al. 2009). Increases in native plants throughout the community in turn improve drought resistance, erosion, and create more "backyard habitat" to further improve connectivity in a positive cycle.

Outside of developed regions, "open space and recreational" land uses are best at providing native plant and animal habitat. As this land is more intensely used, whether that be recreationally or agriculturally, its value as a habitat resource declines. Dry rangeland, which makes up a substantial portion of central New Mexico (see land use map in EMI Impacts Report), also provides significant habitat for plants and animals. Irrigated agricultural lands provide some habitat, but also remove most native plant species and introduce pesticides and pest management tactics that can be harmful to native animal species. Aquatic habitat often depends on return flows from agricultural lands, and maintaining "imperfect" irrigation practices may in fact support these native habitats (Frisvold et al. 2013). Regardless, the presence of any of the three "non-developed" land uses provides a corridor for animals to pass through.

Vegetation Resilience

The Southwestern Region of the U.S. Forest Service (2010) identified the following management strategies to address climate change effects to vegetation.

- Enhance adaptation by anticipating and planning for disturbances from intense storms
- Reduce vulnerability by maintaining and restoring resilient native ecosystems
- Increase water conservation and plan for reductions in upland water supplies
- Utilize markets and demand for small-diameter wood and biomass for restoration, renewable energy, and carbon sequestration

Management that emphasizes diverse, uneven age stands will benefit many forested ecosystems regardless of climate change. A broad mixture of stand conditions ensures the broadest mix of species as it provides sufficient resources to plants and animals (Patton et al. 2014). Greater diversity in species and age of forests would also likely enhance ecosystem resilience to climate change. Historical forests included diverse tree sizes and species, which together provided resilience to several types of disturbances including wildfire. Current risk to dry forests from insect outbreaks is 5.6 times the risk of higher-severity wildfires, with small trees increasing forest resilience to insect outbreaks (Baker and Williams 2015).

An opportunity exists to proactively manage the early successional stages that follow widespread mortality by deliberately reducing synchrony. Ecological succession, a fundamental concept in ecology, refers to more or less predictable and orderly changes in the composition or structure of an ecological community. Asynchrony can be achieved through a mix of activities that promotes diverse age classes, species mixes, stand diversities, genetic diversity, etc., at landscape scales. Early successional stages are likely the most successful (and practical) opportunities for resetting ecological trajectories that are adaptive. Early successional forest habitat is characterized by the growth of bushes and saplings.

The increased variability of streamflow and higher temperatures will reduce the resilience of species and riparian habitats to recover from disturbance. Therefore, preserving a variety of habitats spreads of the risk of adverse climate change impacts (Friggens et al. 2013). Stocking rates may need to be adjusted to adapt to climate change impacts on forage as droughts increase in frequency and severity.

Removing invasive species such as tamarisk and Russian olive may not be not feasible or desirable at all infestations. Chemical and mechanical treatments are expensive and may have negative impacts on the biological communities. The saltcedar leaf beetle (*Diorhabda elongate*) has been used as a biocontrol agent. Shifting management to creating conditions that enhance native species growth may reduce the spread of tamarisk and invasive species along the Rio Grande and other riparian corridors (Friggens et al. 2013). Road closures on National Forests and other lands managed by the federal and state government can minimize the transport of invasive species by vehicles and their passengers.

One measure to increase vegetation resilience to climate change is to plant drought and heat-resistant plant species for erosion control. Extreme weather events will increase risk of "danger trees" falling on power lines and interrupting electrical power service to communities. Accelerated tree thinning along power lines can be undertaken.

Carbon Sequestration

Carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities, which natural resources sequester and therefore help mitigate the impacts of climate change. Carbon sequestration includes any process for capturing and storing atmospheric CO_2 long term. A greater proportion of carbon is stored belowground in rangelands compared with forests or woodlands. Rangelands function as carbon sinks for relatively short periods. Carbon sequestration and storage, as a greenhouse gas mitigation strategy, can be viewed as an ecosystem service. In some regions, simply aiding the spread and rate of encroachment by shrubs such as junipers (*Juniperus* spp.) can capture more carbon. However, shrub encroachment leads to lower biodiversity, higher regional temperatures, increased surface runoff and erosion, and lowered water tables that could ultimately lower the amount of available surface water (Thomey et al. 2014).

The New Mexico Department of Transportation is conducting a study to assess carbon sequestered in soils (soil organic carbon [SOC]) within state highway rights-of-way in New Mexico. One objective of the study is to determine if the vegetation and soils in the rights-of-ways can be managed to obtain carbon credits for the State of New Mexico (Ecosystem Management, Inc. 2013). Practices to enhance carbon sequestration could include mowing schedules, timing of herbicide treatments, retaining water in the rights-of-ways, and planting or seeding.

Resilience of Listed and Proposed Threatened and Endangered Species

Southwestern Willow Flycatcher (Empidonax traillii extimus)

Actions that preserve large and continuous swaths of land provide connectivity for dispersal of species. The water releases from the reservoirs to the Rio Grande can be timed to improve the establishment of cottonwoods, reduce severe fire risk, ensure insect prey availability, and benefit the Southwestern Willow Flycatcher (Friggens et al 2013) as climate changes.

The decline of long-distance migratory birds in Europe and the United States may originate in mistiming of breeding and food abundance due to differences in phenological shifts in response to climate change. To compensate for the resource, it may become necessary to propagate food sources in the interim on US Fish and Wildlife Service Refuges (U.S. Global Climate Science Program 2008).

Rio Grande Silvery Minnow (Hybognathus amarus)

The Bureau of Reclamation has been enabled by federal courts to reduce contract deliveries and restrict water diversions to meet the requirements of the Rio Grande silvery minnow under the Endangered Species Act. Water deliveries also enhance water quality. One of the goals of the restoration plans is to reconnect the floodplain to the river. These measures will increase the resilience of the Rio Grande silvery minnow to climate change.

New Mexico Jumping Meadow Mouse (Zapus hudsonius luteus)

The water deliveries to the Rio Grande benefit riparian vegetation and habitat for the New Mexico jumping meadow mouse. Wetland and riparian restoration projects will increase the resilience of this species.

Mexican Spotted Owl (Strix Occidentalis Lucida)

The Mexican Spotted Owl is highly sensitive to heat and lack of food storage. This species does not migrate. Therefore, it does not respond well to changing temperature and precipitation cues. The presence of suitable foraging and areas and roost sites is a limiting variable. Integrating landscape ecology with forest restoration treatments, economic development, fire management, and infrastructure planning will develop resilience for this species. The Mexican Spotted Owl will likely require linked habitats to endure under projected climate change scenarios (The Nature Conservancy 2010).

Jemez Mountains Salamander (Zapus hudsonius luteus)

Reducing uncharacteristic crown fire, improving current stand conditions, and reducing erosion from severe wildfires and extreme precipitation events will improve the resilience of the Jemez Mountains salamander to climate change.

Yellow-billed Cuckoo (Coccyzus americanus occidentalis)

The Yellow-billed-Cuckoo is endemic to mature riparian habitat. Protecting riparian vegetation with adequate water resources will enhance resilience of this species. Restoration projects that plant riparian species will also be beneficial.

Pecos Sunflower (Helianthus paradoxus)

Protection of groundwater and wetlands will enhance the resilience of this species. Conservation of water will be beneficial.

Policies for Natural Resources

Existing and future policies need to provide managers maximum flexibility, tools and approaches in addressing the effects of climate change (The Heinz Center 2008). In most cases, strong legal and administrative policies are limited (Friggens et al. 2013). Though this is true, the same threats to natural resources have been identified and it is recognized that cooperation, collaboration, adaptation, education, and research are critical to meeting the challenges related to climate change. When determining a course of action, it needs to be in concert with ongoing endeavors. A number of practices that have been recommended include purchase of water rights, transfer of existing development rights away from the riparian corridor, conservation easements, grazing management, floodplain zoning ordinances, and incentive programs to reduce the use of water (Fullerton and Batts. 2003).

The New Mexico Climate Change Advisory Group (CCAG) recommended forestland protection from developed uses, reducing permanent conversion of agricultural and rangelands to developed uses, and converting agricultural lands to grassland or forest. It also recommended expanded use of biomass fuels removed from areas treated to reduce fire risk, as well as further development of programs supporting organic farming (New Mexico Climate Change Advisory Group 2006).

The New Mexico Natural Resource Plan is focused on restoring resiliency to the landscapes that are at most risk and recognizes that close coordination between professionals and the involved jurisdictions is critical (New Mexico Energy Minerals and Forestry Division 2010). The agency lists the following adaption strategies:

- Purchase of water rights
- Transfer existing development rights from riparian corridor to less sensitive areas outside of the riparian corridor or to locations with more resilient characteristics due to low disturbance and human activities
- Conservation easements
- Grazing management.
- Floodplain zoning ordinances
- Incentive programs to reduce use of water (e.g., switch to low water use crops, retrofit irrigation systems to improve efficiency, and create mandates for municipalities)

Grazing management is an important issue in the southwest. Forage quality for livestock is correlated with precipitation. Land managers can take advantage of forage quality during the critical periods of calving and prior to weaning by adjusting the timing of calving. Winter calving, at the time of winter forage growth, is possible in the Southwest because of the mild weather generally present at that time. With higher temperatures and longer growing seasons, this practice may become more feasible (McCollum et al. 2011).

The CCAG recommended placing a greater emphasis on wood products and/or energy production, through appropriate mechanisms, incentives, etc. More specifically, the CCAG recommends utilizing 50 percent or more of the biomass extracted from both WUI and non-WUI areas for wood products and/or energy production by 2012 and continuing through 2020 (New Mexico Climate Change Advisory Group 2006).

The direction of the U.S. Forest Service is to restore and maintain resiliency, including managing for asynchrony, promoting diversity and connected landscapes, and resetting significantly disrupted communities (U.S. Forest Service 2010). The Cibola National Forest is currently revising its Forest Management Plan. The U.S. Forest Service addresses climate change analyses at the strategic national level through the Resource Protection Act (RPA) Assessment. The Bureau of Land Management Rio Puerco Field Office is currently revising its Resource Management Plan. Both planning efforts provide an opportunity to address measures for climate change resilience.

Native nations are taking actions to address climate change by initiating mitigation actions and seeking additional resources for adaptation (Garfin et al. 2013). Federal land management agencies are starting to incorporate climate change in their planning, but efforts are not consistent (Garfin et al. 2013).

It has been proposed that local, state, and federal entities in the Middle Rio Grande establish a pilot program of "Payments for Ecosystem Services (PES)" that rewards landowners for the restoration and protection of critical natural resources and natural water infrastructure. The PES markets include wetland, stream and endangered species habitat mitigation banking, and carbon sequestration projects. PES programs could also be used to increase forest resiliency through thinning and prescribe burns (U.S. Department of Interior 2012).

Summary of Adaptation Strategies for Climate Resiliency

Tenants of adaptation to climate change are to accept uncertainty and manage for desired processes. Heller and Zavaleta (2009) developed a list of recommendations for climate change adaptation strategies for biodiversity management from a review of 112 scholarly records. The top seven recommendations and example actions are listed in Table 4 (Friggens et al. 2013).

Table 4. Climate change adaptation strategies and example actions.

Adaptation Recommendation	Example
Increase connectivity for migration and movement of species	• Design corridors • Remove dispersal barriers • Locate reserves close to each other • Reforestation
Practice intense management to secure populations	• Ensure survival of species by any feasible means
Translocate and captive breeding of species	• Move population to area with more suitable habitat with regard to temperature and precipitation. • Captive breeding
Focus on landscape-level	• Incorporate medium and long-range planning

Adaptation Recommendation	Example
management	• Coordinate species management over broad regions • Promote species dispersal • Establish and review biological corridors to ensure the adaptive capacity of ecosystems and species
Restore and preserve threatened habitats	• Enhance or replace lost ecosystem services (pollination and seed dispersal) • Restore wetlands for flood control • Create artificial wetlands • Restore entire watersheds
Monitor indicator species to understand impacts and improve understanding for future impacts	• Develop monitoring plans
Design reserves able to withstand shifts and disturbances	• Create refugia in areas not expected to experience drastic changes • Protect multiple replicates of habitats • Include representative habitats and species in refuges • Manage for diverse conditions • Maintain genetically diverse and connected communities • Include lands adjacent to rivers or headwaters

The Nature Conservancy and 22 federal, state, and tribal agencies participated in a workshop on managing climate change in the Jemez Mountains (The Nature Conservancy 2009a). The climate change impacts and adaptation strategies are shown in Table 5. The strategies are also applicable other areas of central New Mexico such as the Sandia Mountains.

Table 5. Climate change impacts and adaptation strategies for the Jemez Mountains.

Climate Change Impact	Adaptation Strategy
Increased fire frequency, intensity and size	Use forest thinning and controlled burns to restore forest structure and natural surface fires. Prepare for large crown fires. Increase use of natural ignitions.
Increased disease/insect tree outbreaks and tree mortality.	Thin forests to reduce moisture stress and tree dieback. Increase tree and shrub species and genetic diversity to reduce vulnerability to insect and disease outbreaks.
Reduced frequency of flooding and groundwater recharge and dropping water tables that degrade streamside ecosystems.	Reduce competition from non-native plants by restoring native vegetation and managing grazing by livestock and elk.
Reduced snowpack and more variance in precipitation that reduces stream flows.	Thin forests and set prescribed burns to maximize moisture infiltration into the soil. Provide shade to maintain snowpack and minimize evaporation and sublimation

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APPENDIX 1

Estimated Water Withdrawal Rates for Employment Categories

Employment Sector	2010 Water Withdrawal Volume (acre-feet)	2014 Land Area (acres)	2010 Water Withdrawal Rate (acre-feet per acre)	2010 Water Withdrawal Rate (gal/ft^2)
Commercial	20,137	42,343	0.48	3.56
Institutional	16,110	64,872	0.25	1.86
Industrial	1,342	11,503	0.12	0.87
Wholesale	1,342	2,420	0.55	4.15
Total:	38,931	121,138		