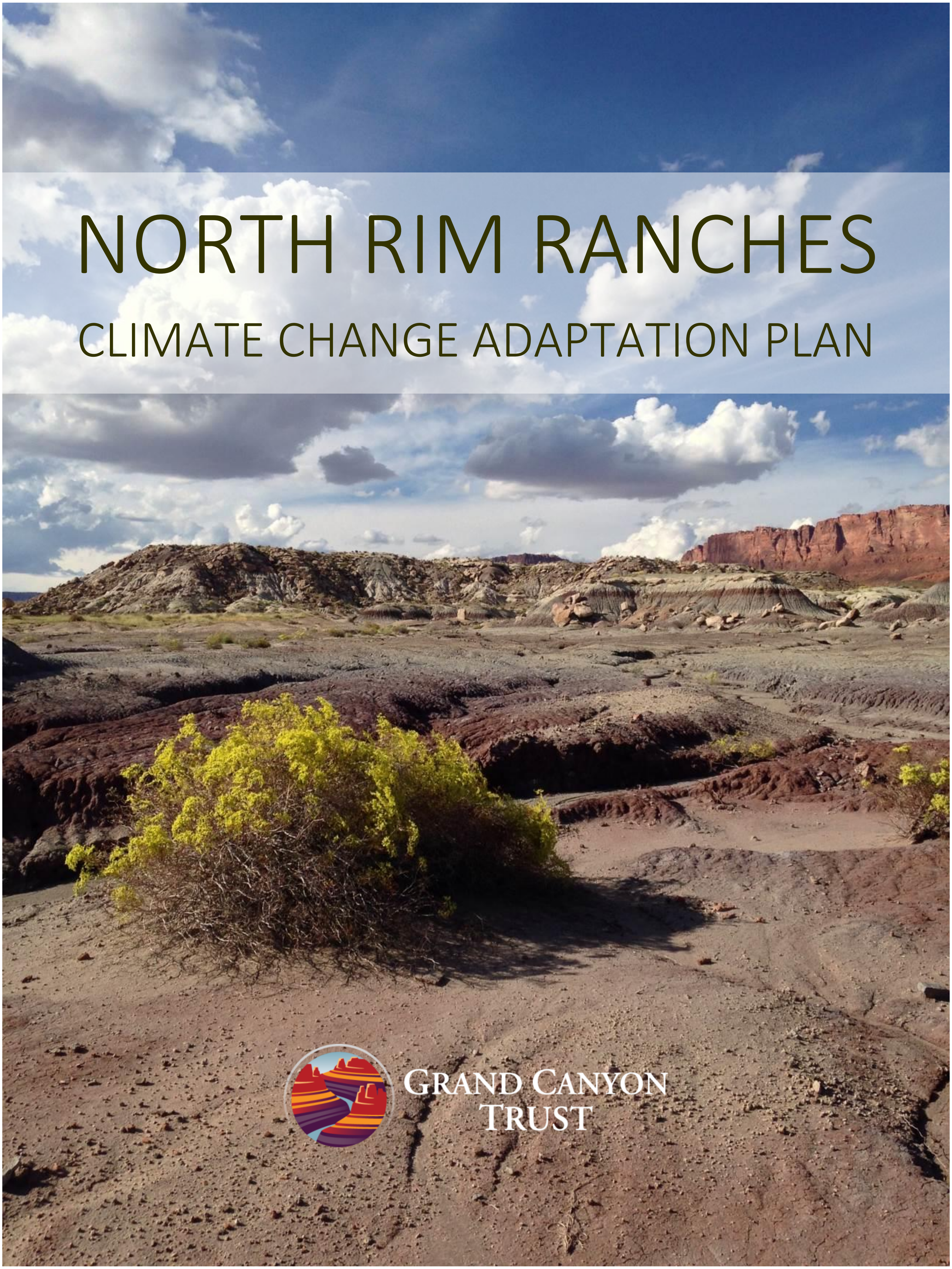
NORTH RIM RANCHES

CLIMATE CHANGE ADAPTATION PLAN



GRAND CANYON TRUST

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Chinle formation on Vermilion Cliffs National Monument. Cerissa Hoglander. 2015.

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The mission of the Grand Canyon Trust is to protect and restore the Colorado Plateau — its spectacular landscapes, flowing rivers, clean air, diversity of plants and animals, and areas of beauty and solitude.

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Executive Summary

The Southwest is considered to be one of the most "climate-challenged" landscapes in the United States (Garfin et al. 2013) and the Colorado Plateau will not be exempt from the impacts of a changing climate. Through the 21st century, the Colorado Plateau is projected to experience hotter temperatures, increased aridity and precipitation variability, and more severe droughts (Seager et al. 2007; Garfin et al. 2013; Cook et al. 2015). Projected climate changes will interact with existing land uses, and each species and ecosystem will respond in unique ways. Yet the extent, timing, and interactions of regional climate impacts are complex and not fully understood. This complexity presents a challenge for those who are working to reduce climate change impacts and to support the ability of species and ecosystems to adapt to change. Taking action based on proactive planning can promote landscape resilience and reduce the impacts from climate change.

We present a landscape-scale climate change adaptation plan that characterizes climate vulnerability and provides a foundation for adaptation action on the North Rim Ranches, a 3,360-km^2 (830,000-acre) landscape of significant ecological and cultural importance on the North Rim of the Grand Canyon. The extent of the North Rim Ranches is defined by the livestock grazing permits held by the Grand Canyon Trust (the Trust) for allotments on public lands managed by the North Kaibab Ranger District of the U.S. Forest Service (USFS) and the Arizona Strip District of the Bureau of Land Management (BLM). Since 2005, the Trust has been the livestock grazing permittee on the North Rim Ranches and, over the last decade, has led efforts to strengthen ecosystem health through conservation-oriented livestock management and collaborative science and restoration (Sisk et al. 2010). Climate changes such as increased risks of prolonged drought and unnaturally severe wildfire present additional challenges to the balancing of conservation objectives with livestock management, as adverse livestock grazing practices can amplify impacts to the landscape (Fleischner 1994). Adaptation actions can minimize the impacts of a changing climate and support resilient responses to current and future conditions across the landscape. This plan focuses on climate change concerns, action recommendations, and implementation opportunities for climate adaptation across the North Rim Ranches. We address five primary objectives:

Objective 1: Assess the vulnerability of the landscape of the North Rim Ranches to climate change impacts.

Objective 2: Develop climate change impact scenarios related to conservation objectives to guide the development of on-the-ground adaptation actions.

Objective 3: Identify and prioritize adaptation actions that can meet conservation objectives within each climate change impact scenario.

Objective 4: Develop monitoring plans with measurable indicators to trigger, inform, and evaluate adaptation actions.

Objective 5: Build support for adaptation implementation through effective communication and collaboration with agency, ranching, and research partners as well as the broader public.

This adaptation plan addresses these five objectives at a landscape scale, laying the groundwork for implementing adaptation action on the ground. We summarize projected climate impacts for the

North Rim Ranches, map landscape-scale climate vulnerability, describe climate impact scenarios, and make recommendations for adaptation (Objectives 1, 2, 3). As monitoring plans and strategies for implementing adaptation are unique to each impact concern and recommended action, we lay out general guidelines for monitoring and building adaptation support (Objectives 4, 5). We also highlight current climate initiatives of the land management agencies and identify opportunities for collaboration among our multiple partners.

This climate change adaptation plan lays out climate change concerns, adaptation recommendations, and next steps for a large public landscape north of the Grand Canyon. While this climate change adaptation plan is by no means comprehensive, we aim for it to be used as a scientific reference and as a guide for integrating climate adaptation objectives into our own conservation planning. We hope that it can serve as a foundation for engaging with agency, ranching, and research partners in collaborative climate adaptation. Our primary climate change impact concerns and adaptation recommendations are listed below.

Summary of Climate Impact Concerns

CONCERN	IMPACT SCENARIO
Drought-impacted water availability	Warming temperatures and increasingly variable precipitation will intensify drought and reduce groundwater recharge and surface water resources. Reduced water availability will heighten vulnerability of species and ecosystems to other environmental and land-use stresses and contribute to resource competition.
Drought-impacted vegetation productivity	Intensifying drought will reduce surface and soil moisture, increasing plant stress and impacting vegetation productivity. Reduced forage resources and altered habitat quality will amplify stresses on wildlife and livestock.
Community composition shifts	Climate change will increase the risk of stress and mortality to species and ecosystems. Community composition will be altered as species are lost or shift in distribution. Such changes will also alter habitat quality and connectivity.
Invasive species spread	Invasive species threaten native biodiversity and increase ecosystem vulnerability to disturbance. Areas currently affected by invasive cheatgrass (*Bromus tectorum*) will likely see further invasion as part of a positive invasive species-wildfire feedback cycle that will be amplified by warming temperatures and precipitation shifts.
Increased risk of unnaturally severe wildfire	Wildfire frequency and severity are projected to increase due to intensifying drought and greater accumulation of fuels. This will impact forest health, alter habitat quality and connectivity, reduce understory vegetation, and encourage non-native species invasions post-disturbance.
Reduced landscape connectivity	Climate-driven community composition shifts, invasive species spread, and increasing risk of unnaturally severe wildfire will contribute to ecosystem and landscape-scale alteration and threaten connectivity among habitats. Roadways and other infrastructure can contribute to fragmentation.
Increased livestock management challenges	Declines in water and forage availability will impact livestock production and increase the risk of adverse grazing impacts. Balancing conservation objectives with livestock management will become increasingly challenging as climate change progresses.

Summary of Adaptation Recommendations

CONCERN	ADAPTATION RECOMMENDATIONS
Drought-impacted water availability	Work with agency and ranching partners, and other stakeholders to prioritize water resources for climate adaptation action based on condition and climate vulnerability as well as conservation, ranching, and public importance.
	Monitor ecological condition and water availability of priority water resources. Link monitoring to water management decisions and triggers for restoration work.
	Restore degraded aquatic and riparian ecosystems.
Drought-impacted vegetation productivity	Support agency and ranching partners in ongoing monitoring of vegetation productivity and forage utilization indicators. Use forage and vegetation monitoring to guide livestock management decisions to protect against overgrazing.
	Collaborate with agency partners to monitor changing vegetation productivity impacts on native wildlife species. Link monitoring information with livestock management decisions and triggers for restoration action.
	Explore grassbanks as a method of alleviating grazing stresses during times of extreme drought.
Community composition shifts	Coordinate with land managers to implement climate-focused forest management.
	Develop and implement native grassland restoration plans in collaboration with land managers.
	Continue to monitor indicators of species and community diversity. Link assessments of landscape-scale climate vulnerability and triggers for protection and restoration.
Invasive species spread	Work with land managers and other partners to continue and/or increase invasive species abatement in climate-vulnerable areas, with particular emphasis on invasive cheatgrass and tamarisk.
	Collaborate with agency and research partners to map and monitor invasive plant species populations.

CONCERN	ADAPTATION RECOMMENDATIONS
	Minimize land-use disturbances from recreation, roadways, and livestock grazing in heavily invaded areas.
	Continue to build knowledge and use best-available science to manage and mitigate invasive species spread and to restore native plant communities.
Reduced landscape connectivity	Work with land managers and other stakeholders to advocate against land-use stresses that can sever connectivity at the Colorado Plateau scale.
	Protect and restore water resources to enhance landscape connectivity, especially in riparian corridors.
	Amplify efforts to mitigate and manage invasive species and unnaturally severe wildfire.
	Work with agency, ranching, and research partners to plan and implement actions that protect and/or restore landscape connectivity across the North Rim Ranches, particularly for focal species.
Increased risk of unnaturally severe wildfire	Work with agency, ranching, and research partners to identify and implement fire management treatments that reduce the threat of unnaturally severe wildfire and allow low- to mixed-severity fire to drive adaptation trajectories.
	Work with land managers to apply post-fire restoration seeding treatments that utilize native species and incorporate climate-resilient plant genotypes.
	Work with land managers to restore historical fire regimes to fire-adapted ecosystems such as ponderosa pine forests and pinyon-juniper woodlands.
Increased livestock management challenges	Work with ranching partners to develop drought risk management.
	Continue to maintain flexible, conservation-oriented rotational grazing patterns and stocking rates through an adaptive management framework linked with site-specific monitoring.
	Identify tools and practices that support climate-conscious livestock management.
	Continue to integrate appropriate livestock grazing considerations into research efforts.
	Collaborate with land managers to monitor ecosystem and rangeland health indicators.

Rationale

Climate is a fundamental driver of ecological processes and human livelihoods. Despite lingering debate over causes and consequences, there is strong scientific agreement on current and projected climate change impacts (IPCC 2014). Global climatic shifts are already apparent and such changes are projected to increase over the 21st century (IPCC 2014). Regional and local observations of climate changes include shorter growing seasons, ongoing drought (e.g., National Tribal Air Association 2009), shifts in river flows, and reductions in mountain snowpack (e.g., Barnett et al. 2008).

Climate change impacts human and ecological communities and will increase the challenges of balancing conservation goals with land use objectives on public lands. Managing livestock grazing sustainably will become especially challenging with climate change and ranching livelihoods will be especially vulnerable to climate impacts (Briske et al. 2015). Livestock grazing is of primary importance to the Trust's ranching partners and many communities on the Colorado Plateau. We at the Trust seek a plan for addressing climate change impacts that balances conservation and livestock management goals into the future.

To reduce the impacts of climate change, we can consider two general categories of response: mitigation and adaptation. Mitigation actions are those that address the magnitude of climate change through reducing greenhouse gas emissions or increasing carbon storage (Joyce et al. 2013; IPCC 2014) and the Trust should continue to support climate mitigation efforts across the Colorado Plateau and beyond. In ecosystems grazed by livestock, mitigation opportunities exist through increasing carbon sequestration in land management and reducing methane (CH_4) emissions from livestock (U.S. Environmental Protection Agency 2014). While the contribution of livestock grazing to greenhouse gas emissions is widely documented (Phetteplace et al. 2001; Herrero et al. 2015), we presume that the current magnitude of carbon emissions from the North Rim Ranches livestock operations to be inconsequentially small and do not evaluate mitigation of climate change in this plan. Instead, we focus on the identification and implementation of climate adaptation actions.

Climate adaptation requires developing and implementing actions that reduce and/or adjust to climate impacts given an uncertain future (Glick et al. 2011; Stein et al. 2013). Adaptation plans include assessing the vulnerability of the land and people to climate change, identifying potential actions to reduce vulnerabilities to climate change, creating monitoring systems to track future changes, and building support for adaptation through effective communication with land managers and the general public. Adaptation planning and action now can reduce the long-term economic costs of climate impacts (ICLEI 2011). In addition, climate adaptation can have useful co-benefits, "no regrets" actions that lessen climate-driven impacts and reduce the vulnerability of lands to other, non-climate disturbances (ICLEI 2011). This adaptation plan sets a strategic foundation for proactively addressing the challenges of public lands conservation and management in the face of climate change.

Introduction

Grand Canyon Trust and the North Rim Ranches

Located in the southern Colorado Plateau, the North Rim Ranches extend approximately 3,360 km^2 (830,000 acres) across predominantly USFS and BLM public lands north of Grand Canyon National Park (**Figure 1**). Ranging from 906 m (2,973 ft) to 2,807 m (9,207 ft) in elevation, this landscape is home to a wide diversity of species and ecosystems with vegetation that spans low-elevation, semi-arid grasslands to mixed conifer and spruce-fir forests. The area is bisected by Highway 89A which runs along the Vermilion Cliffs through House Rock Valley and up to Jacob Lake, Arizona, connecting to Highway 67, the only other primary highway on the north rim of the Grand Canyon.

In 2005, the Grand Canyon Trust purchased the North Rim Ranches' grazing permits which include 44 pastures across eight allotments on the USFS-managed Kaibab National Forest and BLM-managed Arizona Strip District, including the Vermilion Cliffs National Monument. With its mission to protect and restore the Colorado Plateau, the Trust is committed to reducing the historical pressures of livestock grazing and to maintaining and improving the health of these North Rim lands. Specifically, the conservation objectives for the North Rim Ranches are to:

1. Restore productive native grassland, shrubland, woodland, forest, and riparian ecosystems.
2. Protect unique and sensitive natural resources, such as springs, ancient forests and remnants of native grasslands.
3. Restore and maintain thriving, viable populations of a full range of native species.
4. Maintain ecologically and economically sustainable land uses to benefit local economies and support ongoing management activities.
5. Promote inclusive, conservation-based land management by engaging citizens and local, state, tribal, and federal government agencies.
6. Manage livestock grazing in a manner consistent with restoration and maintenance of ecological and scenic integrity.

The Trust uses three conservation-oriented livestock grazing approaches: reduced stocking rates, rotational grazing patterns that include ungrazed reference areas, and modification of ranching infrastructure to reduce wildlife impacts. Currently, the allotments support approximately 600 head of livestock that are managed by Plateau Ranches, LLC in a seasonal rotation guided by the respective agency Allotment Management Plans (U.S. Bureau of Land Management 1982, 1983, 1991; U.S. Forest Service 2013). Two of the eight allotments are closed to livestock grazing while the remaining allotments have a rotational grazing pattern that is aligned with research and restoration goals. This rotational pattern is divided into seasonal summer and winter pastures. Summer pastures are on the top of the Kaibab Plateau and, in the winter, livestock are divided among the House Rock Valley and Paria Plateau pastures. The number of livestock, the timing of grazing season, and the related rotational grazing pattern are based on adaptive management practices and are revised as needed to respond to changes in resource conditions as related to water, drought, wildfire, or vegetation.

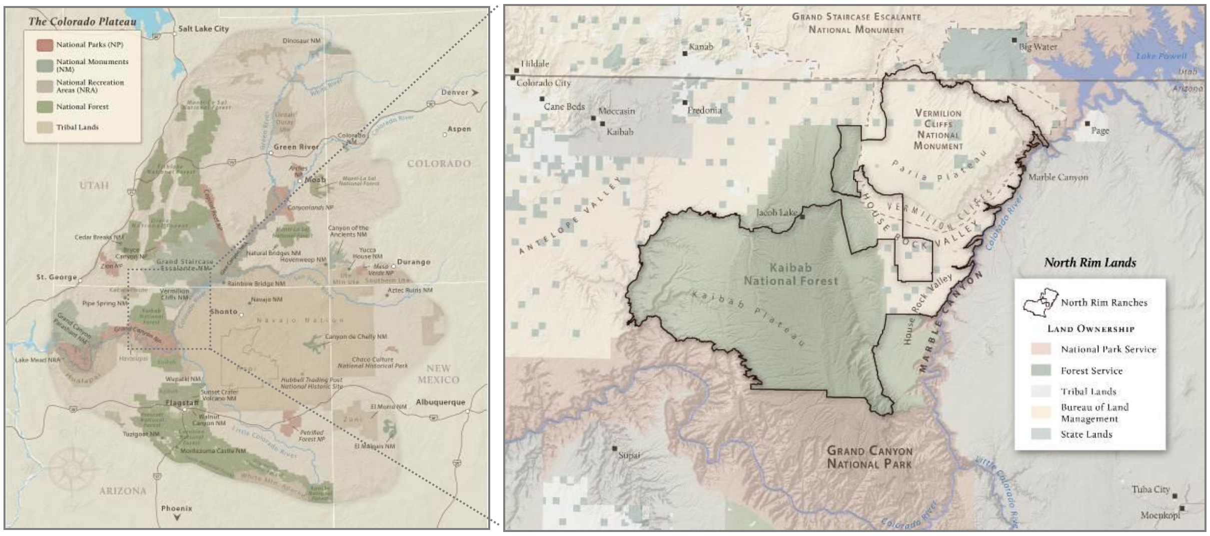

Figure 1 –The Colorado Plateau and the North Rim Lands. The Colorado Plateau is a southwestern United States region of geological uplift across the Four Corners region of Arizona, Utah, Colorado, and New Mexico (left). The North Rim lands are located on the north rim of the Grand Canyon (right) and are federally-managed public lands with several small private and state inholdings. The extent of the North Rim Ranches is defined by the grazing permits held by the Trust on these public lands.

Over the last ten years (2005-2015), the Trust – in collaboration with the USFS, BLM, ranching partners, and researchers – has contributed to new knowledge of ecosystems on the North Rim lands through a collaborative research and restoration program (Sisk et al. 2010). This work has included building knowledge of vegetation, soil, and forest stand characteristics through Baseline Assessment monitoring efforts in 2005 and 2011, mapping and modeling of invasive species, native species inventories, and wildlife habitat models (Sisk et al. 2010). In 2009, the Trust used monitoring data to develop a Restoration Plan focused on conservation objectives, restoration priorities, desired future conditions, monitoring, and livestock management (Albano et al. 2008). Other research has explored the efficacy of native grassland and forest restoration treatments (Sisk et al. 2010; Bernstein et al. 2014; Ray et al. 2014; McMaster et al. 2015); mapped target invasive species to guide management and restoration action (Sisk et al. 2010); and increased information on native wildlife diversity and habitat across the North Rim lands. The Trust has also collaborated with partners to restore key riparian areas on the North Rim lands, including within the Paria River corridor and House Rock Valley, and revitalize springs to reduce impacts from disturbances from livestock grazing and invasive species.

Since 2012, much of this work been completed through the Research and Stewardship Partnership (RSP), a multi-stakeholder collaborative group that supports and conducts science relevant to land management on the North Rim Ranches. The Trust convened the RSP with the USFS, BLM, the United States Geological Survey (USGS), the Arizona Game and Fish Department (AGFD), and several academic research institutions. This effort led to a collaborative Applied Research Plan in 2011 (Grand Canyon Trust et al. 2011) that outlined "an integrated research agenda to inform land and resource management with sound science, enhancing the ability of management agencies to work with their partners and the public to integrate conservation objectives with the sustainable use of public lands on the Colorado Plateau" (Grand Canyon Trust et al. 2011).

This climate change adaptation plan draws on these three key elements – the Baseline Assessment, the Restoration Plan, and the Applied Research Plan – to inform climate adaptation needs, strategies, and priorities across North Rim lands. Many completed and current RSP projects have results that can inform climate adaptation actions; including springs restoration for climate adaptation and native plant "greenstrip" fuelbreaks to reduce the spread of invasive cheatgrass (see www.grandcanyontrust.org).

Geographic Areas of the North Rim Ranches

The Trust groups the USFS- and BLM-managed allotments of the North Rim Ranches into seven ecologically distinct management units: Kanab Creek, the west side of the Kaibab Plateau (West Side), the top of the Kaibab Plateau (Kaibab Plateau), the east monocline of the Kaibab Plateau (East Monocline), House Rock Valley, the Paria Plateau, and the Paria River (**Figure 2**).

Vegetation across the North Rim lands is classified into eleven distinct vegetation types (**Figure 2**). Water resources include springs, seasonal lakes and ponds, and livestock waters such as dirt tanks and troughs. Kanab Creek contains 23 springs as well as its namesake Kanab Creek, a perennial stream that is a tributary of the Grand Canyon's Colorado River. Kanab Creek is federally designated as wilderness and is closed to livestock grazing. The West Side consists of gradual slopes of pinyon pine (*Pinus edulis*), juniper (*Juniperus* spp.), Gambel oak (*Quercus gambelii*), and New Mexican locust (*Robinia neomexicana*) that transition from woodlands at the rim of the Kaibab Plateau to shrublands at lower elevations. While no perennial streams exist on the West Side, 21 springs have been documented with most along the drainages that lead to Kanab Creek. Many of these springs are developed and provide water resources for livestock and/or are used for residential purposes (e.g., the Mangum Springs complex supplies Mangum Camp). The West Side includes the four pastures of the Central Winter Allotment, one of which is closed to grazing.

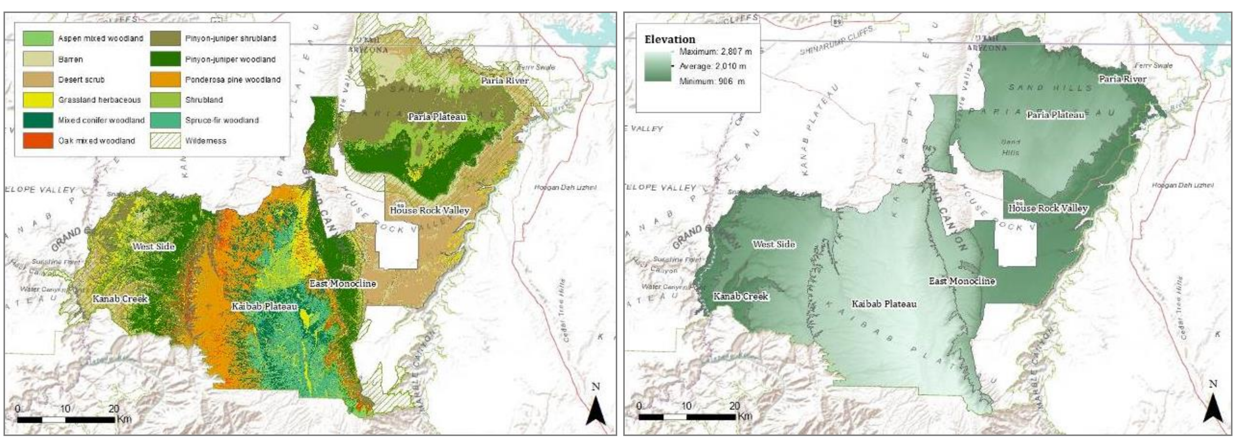

Figure 2 – Geographical and Ecological Characteristics of the North Rim Ranches. The landscape of the North Rim Ranches includes seven distinct geographic areas, three designated wilderness areas, and eleven vegetation types (left). Elevation on these lands ranges from 906 m to 2,807 m (2,972 ft to 9,209 ft; right).

The Kaibab Plateau sits at the highest elevation and contains the only stands of ponderosa pine (*Pinus ponderosa*) and mixed conifer – including white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*) – on North Rim lands. It experiences the coldest winter temperatures, has seasonal snowfall, and has 64 scattered springs and lakes. The Central Summer North and South pastures are located on the Kaibab Plateau and are the primary summer grazing pastures for livestock on the North Rim Ranches. The East Monocline, dominated by pinyon-juniper woodlands, is the transition zone between the Kaibab Plateau and the neighboring House Rock Valley and Paria Plateau. It has only one documented spring, Burro Spring in Burro Canyon. House Rock Valley experiences the warmest temperatures and provides primary winter pastures for livestock. It consists of mostly desert scrub vegetation and has 25 documented springs, most of which are along the base of the Vermilion Cliffs that rise up to the Paria Plateau. Several of these springs are important water resources for wildlife, livestock, and several human communities along the base of the Vermilion Cliffs. The Paria Plateau, second in elevation to the Kaibab Plateau, is dominated by pinyon-juniper shrubland and woodland and extensive slickrock. Pastures on the Paria Plateau provide winter grazing areas for livestock. Six documented springs are present along its west side and several wells on top of the plateau provide seasonal water resources for livestock. The Paria River area is named for the major river that winds through the famous slot canyon of the same name and is a tributary of the Colorado River. Providing extensive riparian habitat, this region is also designated as wilderness and is closed to grazing.

Current Climate on the North Rim Ranches

Like other inland areas of the Southwest, climate on the Colorado Plateau is largely characterized by its diverse topography, the mid-latitude storm track, and the North American monsoon (Garfin et al. 2013). Most of the Colorado Plateau can be classified as semi-arid where temperatures can range from well below freezing in winters to almost 40°C (104°F) in hot summers (Garfin et al. 2013).

Seasonal precipitation varies widely across the Colorado Plateau with total annual precipitation in the region ranging from 270 to 670 mm (11 to 26 in) per year; the driest extremes can be as low as 130 mm (5 in) per year (Hereford et al. 2002). Precipitation is bimodal with peaks in winter and summer monsoons following dry spring and fall periods (Swetnam & Betancourt 1997; Hereford et al. 2002). While the July-September monsoon can provide up to half of the average annual precipitation, Arizona's mountain snowpack contributes significant annual water reserves (Garfin et al. 2013). This snowpack, along with other cool season precipitation, is critical for recharging soil moisture on the Colorado Plateau (Swetnam & Betancourt 1997; Hereford et al. 2002). Water resources in this region, including important rivers like the Colorado and Paria, vary with precipitation patterns and temperature-modulated evaporation and transpiration rates.

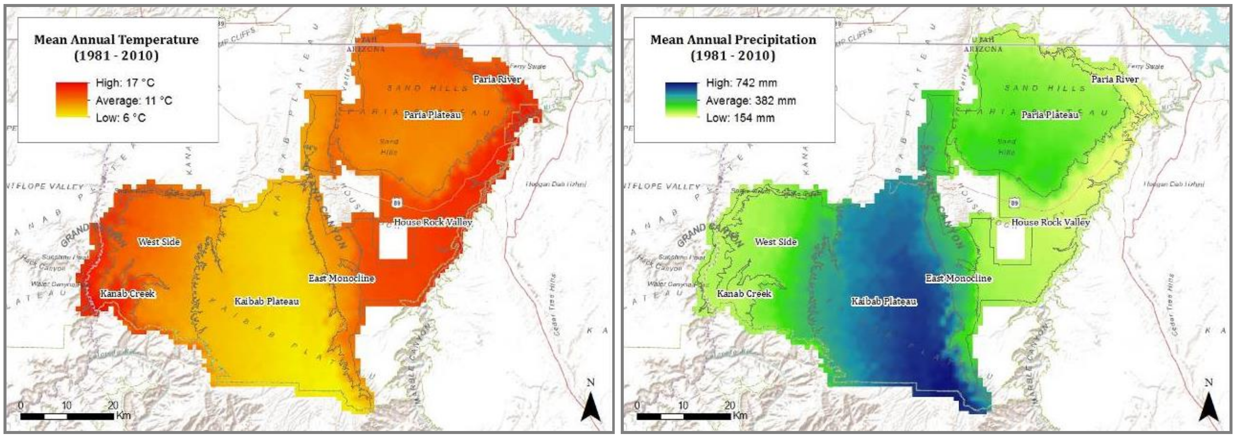

Figure 3 – Current Climate of the North Rim Ranches. We characterized the current climate of the North Rim Ranches using recent (1981-2010) averages for mean annual temperature (°C, left) and mean annual precipitation (mm, right). For mean annual temperature (left), warmer values are darker (red) and cooler values are lighter (yellow). For mean annual precipitation (right), wetter values are darker (blue) and drier values are lighter (yellow). Values are rounded to the nearest whole number (maps based on data from AdaptWest [AdaptWest Project; adaptwest.databasin.org]).

To characterize the current climate at the scale of the North Rim Ranches (**Figure 3**), we modeled mean annual temperature and mean annual precipitation within a Geographic Information System (GIS; ArcMap 10.2, Environmental Systems Resource Institute, Redlands, California, USA). We used data for the most recent 30-year climate "normal" (1981-2010) based on PRISM climate data (PRISM Climate Group; prism.oregonstate.edu) available from AdaptWest (AdaptWest Project; adaptwest.databasin.org). Data were modeled at a resolution of 1 km (3,281 ft), meaning that each pixel of the map represented a 1-km by 1-km area of the landscape. From 1981-2010, mean annual temperature ranged from 6 to 17°C (43 to 63°F) while mean annual precipitation ranged from 154 to 742 mm (6 to 29 in) across the landscape. The Kaibab Plateau was the coldest and wettest geographic area, with average temperature at 8°C (46°F) and average precipitation at nearly 600 mm (24 in) per year. Alternatively, the Kanab Creek, House Rock Valley, and Paria River geographic areas were the warmest and driest, each with average temperatures above 14 °C (57°F) and average precipitation below 300 mm (11 in) per year.

Climate Change Adaptation Planning Objectives

For climate change adaptation planning on the North Rim lands, we reviewed several existing frameworks (Lim et al. 2004; Snover et al. 2007; Williams et al. 2008; ICLEI 2011; Cross et al. 2012; Schmitz et al. 2015). We then developed five objectives for implementing climate adaptation action on the North Rim Ranches.

Objective 1: Assess the vulnerability of the landscape of the North Rim Ranches to climate change impacts.

Assessing vulnerability to climate change impacts based on the best available science and local expert knowledge is the first step in planning for adaptation action. Vulnerability assessments can be qualitative, quantitative, or both (Lim et al. 2004; Cross et al. 2012). The goal of these assessments is to help develop a common understanding of climate-based risks and identify actions that can reduce these risks. We assessed the vulnerability of the landscape of the North Rim

Ranches to climate change through an in-depth literature review coupled with a spatially-explicit, landscape-scale estimation of vulnerability (see *Climate*).

Objective 2: Develop climate change impact scenarios related to conservation objectives to guide the development of on-the-ground adaptation.

Scenario planning involves projecting plausible alternative futures with a broad focus on ecosystem processes and decision support (Galatowitsch et al. 2009). Like vulnerability assessments, scenario planning is based on best available science and local expert knowledge. Scenarios can range from narrative storylines to more quantitative, spatially-explicit analyses using scientific modeling (Cross et al. 2012). Each scenario may identify climatic and non-climatic drivers of change (Cross et al. 2012) and works best when coupled with a management or "preparedness" objective (Snover et al. 2007; ICLEI 2011).

We identified seven impact scenarios by linking known environmental and land-use stresses with anticipated climate change impacts (see *Impact Scenarios and Adaptation Recommendations*). The scenarios are: *Reduced Water Availability, Reduced Vegetation Productivity, Community Composition Shifts and Species Loss, Increased Risk of* Invasive Species Spread*, Increased Risk of Unnaturally Severe Wildfires, Reduced Landscape Connectivity,* and *Increased Livestock Management Challenges*. We summarize current knowledge of existing landscape stresses and, where applicable, link relevant data to our landscape-scale climate vulnerability model.

Objective 3: Identify and prioritize adaptation actions that can meet the conservation objectives within each climate change impact scenario.

Successful adaptation actions can strengthen current conservation efforts to reduce existing stresses on the landscape and improve the capacity to adapt to future climate conditions (Schmitz et al. 2015). Adaptation actions can focus on protecting current patterns of biodiversity, protecting intact natural landscapes, protecting the geophysical setting, maintaining and restoring ecological connectivity, and/or identifying and managing for species dispersal and climate refugia, among others (Mawdsley et al. 2009; Schmitz et al. 2015). These actions can also support climate adaptation in human communities; for example, forest and watershed restoration can reduce the risk of unnaturally severe wildfire in the wildland-urban interface and protect water resources for downstream communities (Erley & Hagen 2010). People can also contribute to public lands adaptation actions by supporting outreach and education and by applying similar actions on private lands (Erley & Hagen 2010; Liverman & Moser 2013).

Prioritizing adaptation actions should be done with consideration of economic, regulatory, and social feasibility as well as of the potential for co-benefits and unintended consequences (Cross et al. 2012). Priority actions can then be implemented in collaboration with other stakeholders to capture broad support and increase effectiveness. Within the *Impact Scenarios and Adaptation Recommendations* section we make recommendations for adaptation actions for each climate impact scenario and identify where these can overlap with existing conservation efforts.

Objective 4: Develop monitoring plans with measurable indicators to trigger, inform, and evaluate adaptation actions.

A monitoring plan within an adaptive management framework can identify intervention points and inform decision-making (Galatowitsch et al. 2009). Indicators within a monitoring plan should link to conservation objectives and, where possible, feed back into models of vulnerability (Conroy et al. 2011), allowing for new learning to influence next steps. Monitoring can also help refine climate scenarios and evaluate the effectiveness of adaptation actions. While we do not include detailed monitoring plans in this adaptation plan, we do outline general recommendations for monitoring ecological, rangeland health, and climate indicators that can support monitoring climate adaptation (see *Monitoring*).

Objective 5: Build support for adaptation implementation through effective communication and collaboration with agency, ranching, and research partners as well as the broader public.

Building a network of collaborators provides a durable framework for a coordinated response to climate change impacts. Stakeholder expertise can be used to refine climate impact scenarios, and facilitate implementation (Lim et al. 2004). Engagement with the general public is also important to build support for climate change preparedness. Communications should describe climate change impacts that have already been observed and impacts that are expected, identify examples of other adaptation planning efforts, recommend specific actions, and communicate challenges and uncertainties associated with climate change and adaptation (Snover et al. 2007).

We identify opportunities for collaboration with land managers and other stakeholders in the *Opportunities for Building Support and Implementing Adaptation Action* section. We highlight where existing conservation and management objectives can overlap with climate adaptation goals. In addition, we make suggestions for broader communications that emphasize networking and knowledge-sharing to strengthen climate adaptation on North Rim lands and across the Colorado Plateau.

Climate Change Vulnerability

To meet our first adaptation objective and assess the vulnerability of the North Rim Ranches landscape to climate change impacts, we conducted an in-depth literature review and modeled a spatially-explicit estimation of climate change stress and vulnerability. At the time of developing this plan, climate change projection data and literature specific to the North Rim Ranches landscape were limited. Therefore, we reviewed climate change projection information and utilized data for the southwestern United States and, when available, for the Colorado Plateau.

Projected Climate Change for the North Rim Ranches

Regional climate change projections for the Southwest and the Colorado Plateau are important for estimating future conditions on North Rim lands. The *Assessment of Climate Change in the Southwest United States* report (Garfin et al. 2013), prepared for the United States' National Climate Assessment in 2013, is an important reference for the region and is a primary resource for this adaptation plan.

Compared to other regions of the United States, multiple regional climate models show that the Southwest will likely experience some of the greatest climate change into the mid and late 21st century (Diffenbaugh et al. 2008). Across the Southwest, climate change is already occurring – the 2000-2009 period registered annual temperatures warmer than any decade of the 20th century

(Garfin et al. 2013). Since 2010, temperatures have continued to rise (IPCC 2013; Karl et al. 2015). In the Southwest, surface temperatures are anticipated to continue to warm and to exceed the historical range of variability by the 2030s (Garfin et al. 2010). Under a high emissions scenario, mean annual temperatures in the Southwest are projected to warm by 2.8 to 5°C (5 to 9°F) by the end of the century (Garfin et al. 2013). Summer temperatures are projected to warm more compared to other seasons while winter cold snaps are projected to become less frequent, though not necessarily less severe (Garfin et al. 2013).

While projections of warming temperatures are relatively uniform across the Southwest, projections of overall precipitation change vary (Garfin et al. 2013). Historically, mean annual precipitation has exhibited greater variability (i.e., when and where precipitation occurs) in the Southwest than in other areas of the United States (Garfin et al. 2013). This high variability is anticipated to continue in the region through the rest of the century (Seager et al. 2007; Diffenbaugh et al. 2008; Garfin et al. 2013) with more frequent extreme droughts and floods (Cook et al. 2015). Seasonally, precipitation changes are projected to take the form of increases in winter precipitation (Christensen & Lettenmaier 2007; Garfin et al. 2013), although winter precipitation may actually decrease substantially at low elevations and increase at high elevations (Kopytkovskiy et al. 2015). Despite the variation in precipitation projections across models (Garfin et al. 2013), there is general agreement that snowpack (and related soil moisture and runoff) will be reduced across the Southwest (Barnett & Pierce 2009; Cayan et al. 2010; Kopytkovskiy et al. 2015). This is expected to occur particularly in the low to middle elevations of the southern Colorado Plateau (Hoerling et al. 2013), including in the North Rim Ranches region (Christensen & Lettenmaier 2007).

With projected shifts in precipitation occurrence and timing, declines in river flow, runoff, and soil moisture are expected to worsen (Hughson et al. 2011; Garfin et al. 2013). Recent drought in the Colorado River Basin has led to the lowest accumulated deficit in water flow at Lee's Ferry in over 100 years of flow monitoring (Cayan et al. 2010; Garfin et al. 2013). These multi-year droughts have a high likelihood of continuing or worsening through the remainder of the century (Cayan et al. 2010). Warmer temperatures coupled with changes in precipitation will lead to increased evaporation and less surface moisture (Seager et al. 2007; Cayan et al. 2010). These changes will amplify drought conditions as part of a significant drying trend that is projected to continue for the region (Seager et al. 2007; Cayan et al. 2010) and lead to an increased likelihood of unprecedented multi-decadal droughts after 2050 (Cook et al. 2015). A drying trend coupled with increased precipitation variability can substantially alter the current hydrologic cycle, reduce groundwater recharge, and further stress water resource availability (Archer & Predick 2008; Hughson et al. 2011). These shifts point toward decreasing soil moisture and increased vulnerability of vegetation to other disturbances, such as disease and pest outbreaks (Garfin et al. 2010).

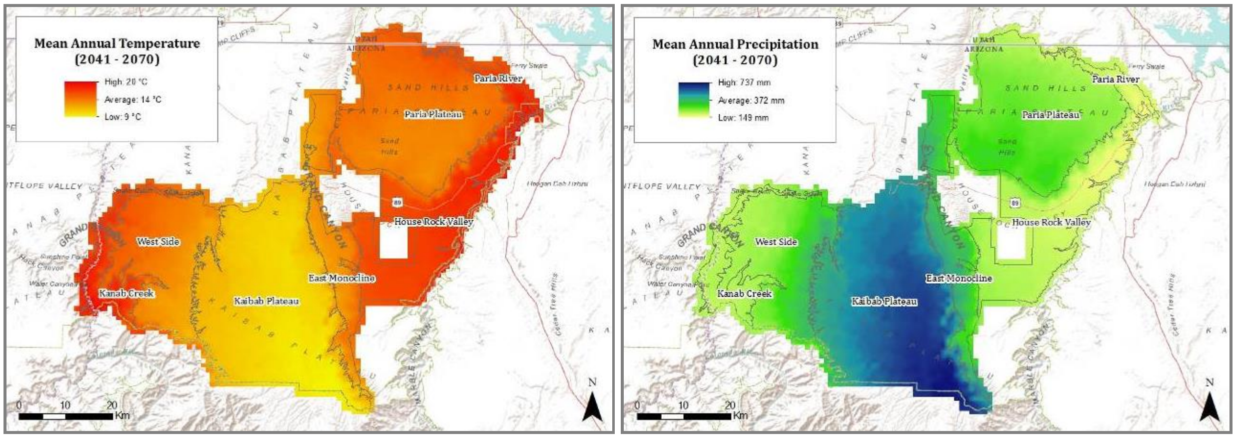

Figure 4 – Projected Climate for the North Rim Ranches. We characterized projected climate for the North Rim Ranches using mid-century projections (2041-2070) for mean annual temperature (°C, left) and mean annual precipitation (mm, right). For mean annual temperature (left), warmer values are darker (red) and cooler values are lighter (yellow). For mean annual precipitation (right), wetter values are darker (blue) and drier values are lighter (yellow). Values were rounded to the nearest whole number (maps based on data from AdaptWest [AdaptWest Project; adaptwest.databasin.org]).

To further characterize projected climate changes for the North Rim Ranches, we modeled climate projections within GIS for mean annual temperature and mean annual precipitation using data based on a regionally-downscaled CMIP5 model ensemble for mid-century (2041-2070) available from AdaptWest (AdaptWest Project; adaptwest.databasin.org). We used the representative concentration pathway (RCP) of 8.5, the highest of four pathways (relative to RCPs 2.6, 4.5, and 6.0) representing greenhouse gas emissions for the 21st century without additional efforts to constrain emissions (IPCC 2014). Data were modeled at a resolution of 1 km (3,281 ft); each pixel of the map represented a 1-km by 1-km area of the landscape. Based on the model calculations, the 2041-2070 time period exhibits mean annual temperatures of 9 to 20°C (48 to 68°F) and mean annual precipitation of 149 to 737 mm (6 to 29 in) for the landscape of the North Rim Ranches. The distribution patterns of temperature and precipitation across the North Rim Ranches are consistent with those of the current climate: the Kaibab Plateau remains the coldest and wettest while Kanab Creek, House Rock Valley, and the Paria River remain the warmest and driest (**Figure 4**).

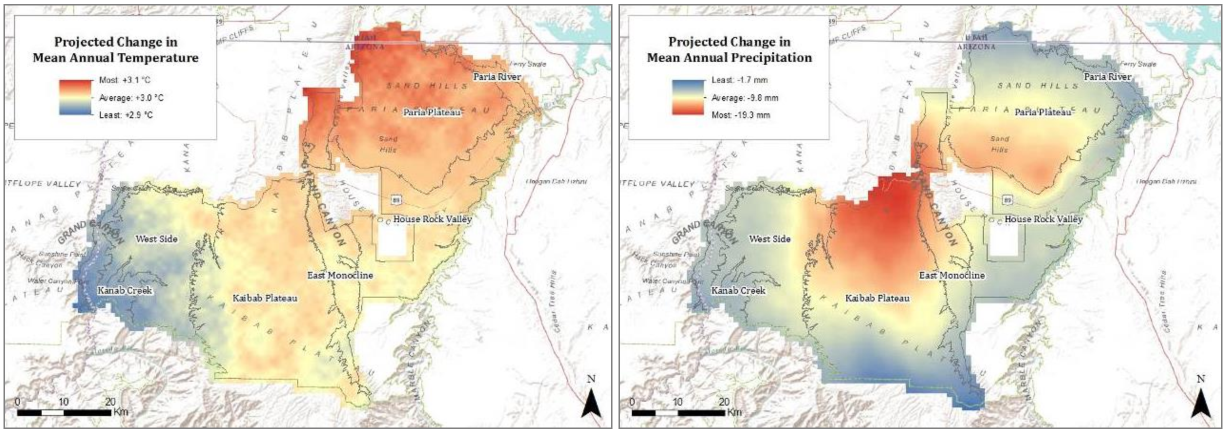

Figure 5 – Projected Climate Change for the North Rim Ranches. We characterized climate change by mid-century (2041-2070) for the North Rim Ranches using mean annual temperature (°C, left) and mean annual precipitation (mm, right). For both mean annual temperature (left) and mean annual precipitation (right), more change is depicted in red while less change is depicted in blue. Values were rounded to the nearest whole number (maps based on data from AdaptWest [AdaptWest Project; adaptwest.databasin.org]).

To understand climate change across the North Rim Ranches, we compared our models of projected climate (**Figure 4**) to our models of current climate (**Figure 3**) by calculating a per-pixel difference within GIS. For changes in mean annual temperature, we calculated a +2.9 to +3.1°C (+5.2 to +5.6°F) increase across the landscape (**Figure 5**). We calculated the most warming to occur for the Paria Plateau and northern portion of the East Monocline and the least warming to occur for the West Side and Kanab Creek. The warming projected for the North Rim Ranches is consistent with the literature, albeit on the higher end of other projected ranges. Warming projections based on a CMIP3[1] model basis from Garfin et al. (2013) range from +1.1 to +3.3°C (+2 to +6°F) for similar time periods (2041-2070 compared to 1971-2000).

For changes in mean annual precipitation, we calculated a -1.7 to -19.3 mm decrease across the landscape (**Figure 5**), representing approximately a 0.1 to 5.0 percent change (compared to current mean annual precipitation). We calculated the most change to occur on the northern portion of the Kaibab Plateau, northern portion of the East Monocline, and the southern portion of the Paria Plateau. Our calculations of small but negative average change are consistent with the literature (Garfin et al. 2013); the highest calculated percent change is slightly larger in magnitude than the projected 4 percent change for the Southwest overall by 2055 (Garfin et al. 2013).

Climate Change Stress and Vulnerability for the North Rim Ranches

Vulnerability is defined as the degree to which a species or ecosystem is susceptible to and unable to cope with adverse effects of climate change (IPCC 2014). To assess the vulnerability of the North

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[1] The CMIP5 model, the basis for analysis in the IPCC's Fifth Assessment Report (IPCC 2014), is considered to have warmer projections for RCP8.5 as compared to the A2 scenario parallel in the CMIP3 model, the basis for analysis in the IPCC's Fourth Assessment Report (IPCC 2007). Comparisons of the CMIP3 and CMIP5 models can be found in: U.S. National Oceanic and Atmospheric Association (2015).

Rim Ranches landscape to climate change, we employed a widely-accepted framework for assessing vulnerability to climate change based on three components: climate change exposure, sensitivity, and adaptive capacity (Smit & Wandel 2006; Glick et al. 2011). We define these three components below as they are used in this adaptation plan and describe our methods in detail in *Appendix A:*

Climate Vulnerability Assessment.

TERM	DEFINITION	REPRESENTATION
Exposure	Exposure is a measure of the magnitude, rate, and character of climate change that a species or ecosystem experiences (Glick et al. 2011).	Exposure was modeled using the difference between projected and current climate metrics based on data from AdaptWest (AdaptWest Project; adaptwest.databasin.org).
Sensitivity	Sensitivity is the degree to which a species or ecosystem is affected, whether adversely or beneficially, directly or indirectly, by climate variability or climate change (Glick et al. 2011; Finch 2012; IPCC 2014).	Sensitivity was modeled using a measure of land facet diversity developed by C. Albano (Albano 2015) which can act as a geophysical buffer for climate change exposure.
Adaptive Capacity	Adaptive capacity is the ability of a species or an ecosystem to cope with the impacts of climate change without losing life or some critical function (Glick et al. 2011; Finch 2012).	Adaptive capacity was modeled based on ecological integrity using a metric of landscape intactness developed by D. Theobald (2012).

We first modeled climate change stress as a function of exposure and sensitivity to climate change within GIS. We then modeled vulnerability to climate change by combining climate stress and climate adaptive capacity. We modeled each component for the extent of the North Rim Ranches landscape using a 1-km (3,281-ft) resolution, the coarsest resolution of our input data. For display purposes only (i.e., smoothing), we re-scaled final outputs to a 270-m (886-ft) resolution. We represented the final climate stress and vulnerability estimations as a scaled, per-pixel score ranging from 1 (worse; higher stress or vulnerability) to 10 (better, lower stress or vulnerability). Our spatially-explicit assessments of relative climate stress and vulnerability across the North Rim Ranches are depicted in **Figure 6**.

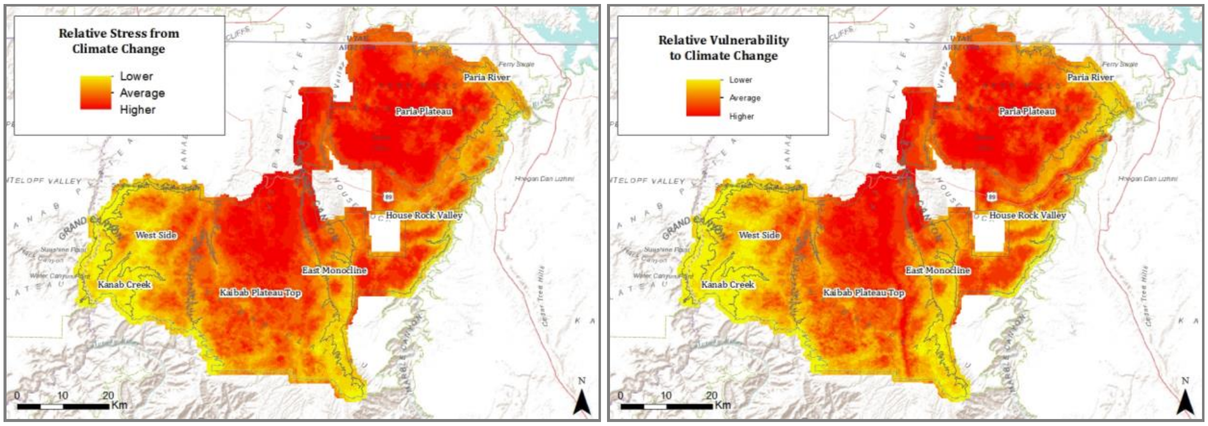


Figure 6 – Relative Climate Change Stress and Vulnerability on the North Rim Ranches. We mapped relative climate stress (left) and relative climate vulnerability (right) for the North Rim Ranches based on landscape-scale estimates of exposure, sensitivity, and adaptive capacity. Areas in red (darker) represent areas of higher stress or vulnerability relative to the rest of the landscape, while areas in yellow (lighter) represent areas of lower stress or vulnerability.

We found substantial variation across the North Rim Ranches for our estimations of relative climate stress and vulnerability (**Figure 6**). The northern portion of the Kaibab Plateau, the southern portion of the Paria Plateau, and much of House Rock Valley and the East Monocline exhibit both higher stress and higher vulnerability relative to the rest of the landscape. Kanab Creek and portions of the Paria River and West Side had lower climate stress and vulnerability relative to the rest of the landscape.

This vulnerability assessment identifies areas on the North Rim Ranches landscape that are projected to have higher climate stress and lower adaptive capacity and may therefore be more vulnerable to climate change (relative to other areas on the landscape). Importantly, this vulnerability assessment does not indicate that areas of lower climate vulnerability will not be adversely affected by climate change, nor that only higher climate vulnerability areas should be the focus of adaptation action. On the contrary, climate change impacts will have effects across the North Rim Ranches (see *Impact Scenarios and Adaptation Recommendations*). At a landscape scale, higher vulnerability areas are expected to experience climate changes at a faster rate (Loarie et al. 2009; Ackerly et al. 2010) while lower vulnerability areas may be areas with the greatest potential for climate refugia (Dobrowski 2011). This landscape-scale climate vulnerability assessment is intended to serve as a coarse-scale tool in the adaptation planning process. It provides a means by which global-scale models of climatic changes can be translated into estimations of local impacts via finer-scale assessments at the species or ecosystem level. This climate vulnerability map can support the identification of priority areas for adaptation on the North Rim Ranches, but should not be used as the sole reason for decision-making.

To demonstrate applications of this climate vulnerability assessment, we bridged landscape-level vulnerability with specific impact concerns associated with climate-compounding environmental and land-use stresses in the *Impact Scenarios and Adaptation Recommendations* section below. Where relevant spatial data were available, we created "Data Resources" sidebars that overlaid the climate vulnerability model with information relevant to each impact scenario. The data resources provide examples of landscape-level vulnerability overlaid with resources such as vegetation and water or disturbances from invasive cheatgrass that can support future species- or ecosystem-specific planning.

Impact Scenarios and Adaptation Recommendations

To meet our second climate adaptation objective, we identified seven primary climate impact scenarios by linking known environmental and land-use stresses with anticipated climate change impacts at the scale of the North Rim Ranches. We addressed our third climate adaptation objective by providing recommendations for adaptation action in each of the impact scenarios below.

Impact Scenario Framework

Historical environmental disturbances, land uses, and land management have dramatically altered the ecological processes and habitat quality in many areas of the North Rim lands (Albano et al. 2008; Sisk et al. 2010). Many of these stresses persist in the region and related impacts are likely to be amplified with ongoing climate change. For example, increasing drought can lead to more vegetation mortality that creates more fuels, increasing the risk of unnaturally severe wildfire. The relationships among stresses and impacts are complex, but it is important to develop an understanding of how these interact on the landscape to develop climate impact scenarios. To do this, we first selected a subset of the environmental and land-use stresses described in detail in the Restoration Plan for each of the geographic areas on the North Rim lands (Albano et al. 2008, **Figure 7**).

Environmental Stresses	Kanab Creek	West Side	Kaibab Plateau	East Monocline	House Rock Valley	Paria Plateau	Paria River
Drought	X	X	X	X	X	X	X
Erosion	X						X
Flooding	X						X
Invasive Species	X	X	X	X	X	X	X
Sediment Deposition	X						X
Wildfire		X	X	X		X	
Land-use Stresses	Kanab Creek	West Side	Kaibab Plateau	East Monocline	House Rock Valley	Paria Plateau	Paria River
Livestock Grazing (On- or Off-site)	X	X	X	X	X	X	X
Recreation	X		X		X	X	X
Transportation (e.g. Roadways)		X	X		X	X	
Water diversion (On- or off-site)	X	X	X	X	X	X	X

Figure 7 – Environmental Stresses on the North Rim Ranches. We identified the environmental and land-use stresses in each of the geographic areas of the North Rim Ranches based on the Restoration Plan (Albano et al. 2008) and the Trust's developed springs location data.

To understand the interactions among existing environmental stresses and impacts, we generated concept maps using CMAP Tools (CMAP Tools 6.01.01, Institute for Human and Machine Cognition, Pensacola, Florida, USA). These maps demonstrate the relationships among stresses and impacts in each of the seven geographic areas. We then highlighted each of the existing stresses/impacts that are influenced directly or indirectly by climate change. We generated two concept maps: terrestrial stresses for the West Side, Kaibab Plateau, East Monocline, House Rock Valley, and Paria Plateau (**Figure 8**), and aquatic/riparian stresses for Kanab Creek and the Paria River (**Figure 9**). While these concept maps are not comprehensive, they depict primary concerns and the mechanisms by which impacts materialize.

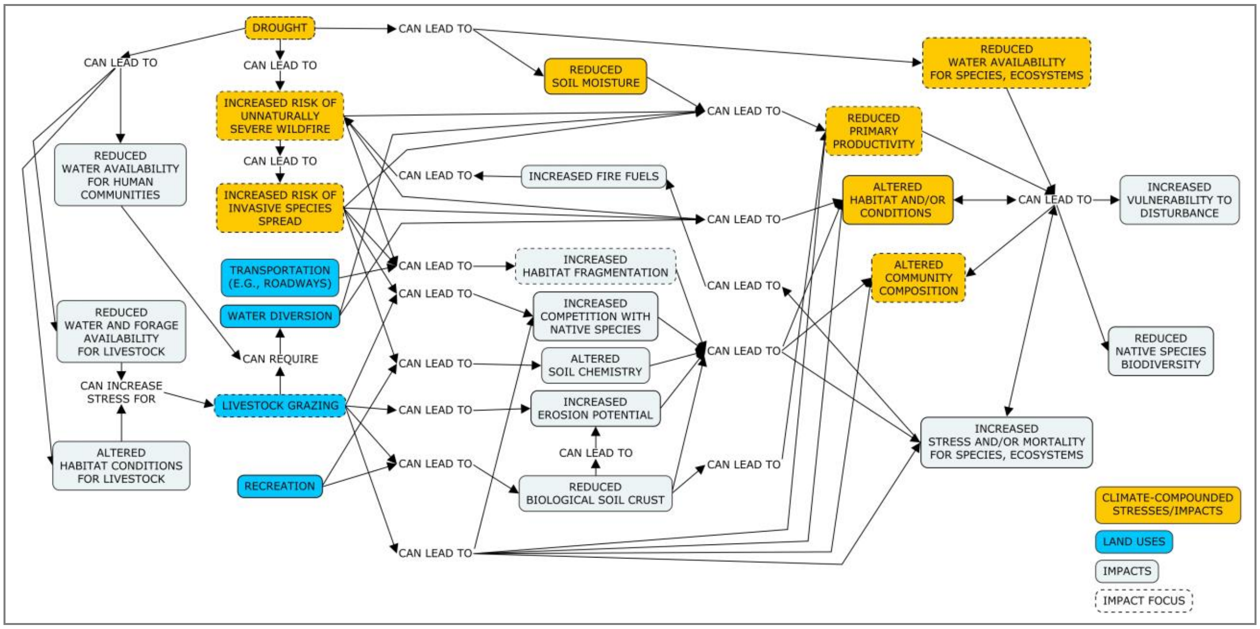


Figure 8 – Concept Map of Stressors and Impacts for Terrestrial Ecosystems on the North Rim Ranches. This concept map depicts relationships between stresses and impacts on the West Side, Kaibab Plateau, East Monocline, House Rock Valley, and Paria Plateau geographic areas. Impacts outlined with a dotted line are the foci for the impact scenarios below.

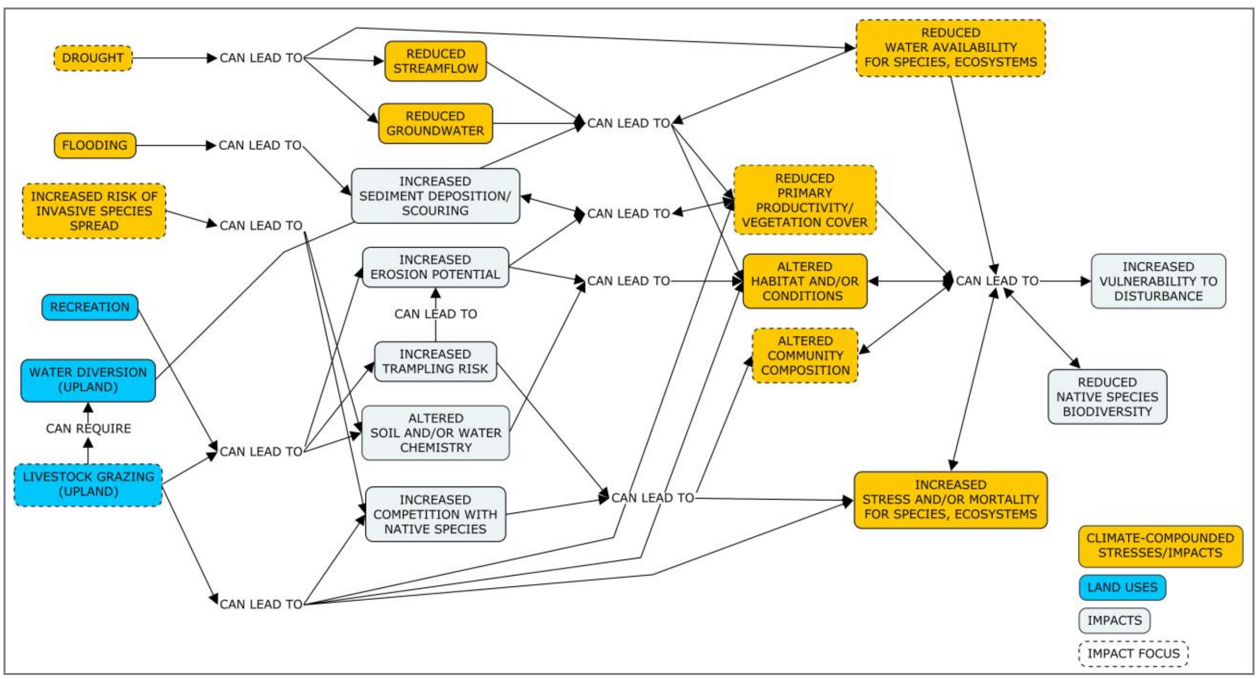


Figure 9 – Concept Map of Stressors and Impacts for Aquatic and Riparian Ecosystems on the North Rim Ranches. This concept map depicts relationships between stresses and impacts on the Kanab Creek and Paria River geographic areas. Impacts outlined with a dotted line are the foci for the impact scenarios below.

Using these concept maps, we developed impact scenarios through which species and ecosystem stresses and/or mortality are expected to increase and vulnerability to climate change and other disturbance are likely to be amplified. These seven impact scenarios include: *Reduced Water Availability, Reduced Vegetation Productivity, Community Composition Shifts and Species Loss, Increased Risk of Invasive Species Spread, Increased Risk of Unnaturally Severe Wildfires, Reduced*

Landscape Connectivity, and *Increased Livestock Management Challenges*. Below, we describe each impact scenario. We couple each of these scenarios with adaptation action recommendations that can address climate-compounding stresses and reduce ecosystem and landscape-scale vulnerability to climate change.

Reduced Water Availability

Impact Scenario

Warming temperatures and more variability in precipitation events increase evaporation, reduce surface and soil moisture, and constrain groundwater recharge (Seager et al. 2007; Archer & Predick 2008; Cayan et al. 2010; Hughson et al. 2011). Such projected conditions will serve to further impact water resource availability in this already arid region and contribute to increased vulnerability of species and ecosystems to other environmental and land-use stresses.

On the North Rim lands, water resources include the Paria River, Kanab Creek, and over 140 documented springs, wet meadows, ponds, and lakes that provide important habitat. Many of the water resources on North Rim lands provide rare aquatic and riparian habitat and/or provide water resources for livestock, human community, or agency needs. Even small climatic shifts will lead to more stress on both ecosystems and livestock management activities, potentially increasing competition for resources. Riparian ecosystems are typically hotspots of biological diversity and can provide climate refugia for some species, especially in arid landscapes (U.S. Forest Service 2014a). As climate change progresses, riparian ecosystems will be increasingly important to adaptive capacity at species- and landscape-scales, but may also be particularly vulnerable to climate change due to their intrinsic sensitivity to climate changes and historical degradation (Capon et al. 2013).

Drought impacts in the Kanab Creek and Paria River geographic areas are of particular concern. Based on the Restoration Plan’s state-and-transition models, reduced water availability in the Kanab Creek and Paria River geographic areas can lead to reduced streamflow and streamflow variability (Albano et al. 2008). These impacts can alter existing erosion and sediment deposition patterns, favor invasive species such as tamarisk and Russian olive, change aquatic and riparian habitat, and alter the species composition of associated aquatic and riparian ecosystems (Albano et al. 2008). Significant changes in erosional and depositional patterns can begin to affect stream channel structure and bank stability and to introduce an arroyo cut-and-fill feedback cycle that induces channel incision, reduces bank stability, and further depletes water resources. Over time, water depletion can substantially reduce aquatic and riparian habitat. Species composition within remaining riparian habitat would likely shift toward dominant invasive species such as tamarisk (Albano et al. 2008).

For springs, lakes, and wet meadows across the rest of the North Rim lands, climate change will alter the timing and duration of water availability, shifting some surface resources from perennial to ephemeral. Reduced water availability will likely stress already limited aquatic and riparian habitat. This will subsequently alter habitat conditions for dependent species on-site as well as decrease connectivity for wider-ranging wildlife. Reduced water availability can increase competition for resources among wildlife and with livestock, and can increase stress or mortality for those species and ecosystems that are unable to resist or adapt to the change. Moreover, spring ecosystems that have historically been adversely impacted by invasive species introductions, erosion, or other degradation are likely to be more sensitive to additional water reductions than springs with greater ecological integrity.

Many of the water resources on the West Side, Kaibab Plateau, and in the House Rock Valley also support livestock during summer or winter pasture rotations as well as human use in USFS camps, ranch houses, and/or the nearby northern Arizona communities of Jacob Lake, Vermilion Cliffs, and Cliff Dwellers. On the Paria Plateau, where livestock waters are mostly pumped from wells, depleted water resources could result in a deepening groundwater table and dry wells, further challenging livestock management (see *Increased Livestock Management* Challenges). Any actions that increase demands for water use (i.e., water diversion) across the North Rim lands – whether related to livestock use, wildlife use, or human use – can also place additional stresses on ecosystems that, over time, are likely to be increasingly vulnerable. Water shortages among multiple stakeholders have been identified by the USFS on the Kaibab National Forest as a climate concern (U.S. Forest Service 2014a) and may lead to more complex land management decisions.

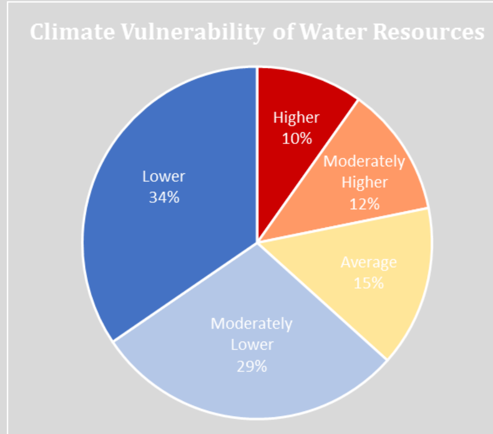
Recommended Adaptation Actions

Protect water resources from environmental and land-use stresses. Protection of water resources should be a primary focus of climate adaptation actions. Water resources affected by environmental and land-use stresses will be more sensitive to climate change impacts. Reducing on-site impacts as well as off-site water diversions or other non-ecosystem water uses are important management considerations in the face of climate change. Related adaptation actions could include managing recreation around priority spring ecosystems, maintaining fences (e.g., around lakes), or avoiding new water diversions and lessening the impact of existing systems (e.g., pipeline leak repair).

Work with agency and ranching partners and other stakeholders to prioritize water resources for climate adaptation action based on condition, climate vulnerability, and conservation, ranching, and public importance. The Trust's data archives have location information for over 140 water resources on the North Rim Ranches. Assessments of ecosystem current condition exist for some of these water resources. Additional inventory data for this region and beyond can be obtained from the online database maintained by the Springs Stewardship Institute (Springs Stewardship Institute; springstewardshipinstitute.org) and/or through future collaborative monitoring. Protection and restoration needs can be derived from these condition assessments and can be coupled with landscape-scale climate vulnerability to estimate risk at an ecosystem level (see *Data Resources* sidebar in this section). We should collaborate with agency and ranching partners to identify priority water resources based on condition and vulnerability as well as ecological value and other stakeholder needs.

DATA RESOURCES

There are over 140 natural waters resources documented on the North Rim Ranches, including springs and lakes. We compared water resource locations with our climate vulnerability assessment to guide adaptation priorities. As shown in the figure to the right, 22% of waters were in relatively higher vulnerability areas while 63% were in relatively lower vulnerability areas.



Monitor ecological condition and water availability of priority water resources. Link monitoring to livestock water management decisions and triggers for restoration work. We should collaborate with agency and ranching partners as well as regional experts (e.g., Springs Stewardship Institute) to support the ongoing monitoring of priority water resources. This monitoring would focus primarily on changes in ecosystem health indicators and water availability. The information obtained from this type of monitoring must be linked to decisions about livestock water management and rotational grazing patterns to prevent both water-related stresses on livestock and increased competition with wildlife.

Restore degraded aquatic and riparian ecosystems. Restoration can reduce the impacts of environmental and land-use stresses in riparian and aquatic ecosystems as well as reduce the sensitivity of these ecosystems and associated species to drought and reduced water availability. Restoration work can include reducing invasive species, mitigating erosion risk, and reducing the impact of water diversions.

For the geographic areas of Kanab Creek and Paria River in particular, ongoing invasive species reduction targeting tamarisk and Russian olive should be a primary focus. Reducing non-native plant cover to below 5% can reduce the threat of significant changes to stream morphology, flow, and erosion and sediment deposition patterns (Albano et al 2009). Along the Paria River and at several spring sites, the Trust has worked to improve habitat quality by reducing invasive species cover, mitigating erosion risk, and lessening the effect of water diversions through collaboration with AGFD, U.S. Fish and Wildlife Service, and many volunteers. Similar approaches can be applied to invasive species in Kanab Creek and at other priority areas, ideally in collaboration with agency and ranching partners as well as land managers in neighboring areas of the Upper Colorado River watershed, including the National Park Service in Grand Canyon National Park. Site-specific restoration plans need to be coupled with effectiveness monitoring. In addition, actions should maximize the opportunities to engage neighboring communities and volunteers in citizen science and restoration efforts.

The specifics of projected hydrological system and precipitation variability shifts with climate change on North Rim lands are uncertain, but climate change will reduce water availability in an already arid region. Taking "no regrets" actions to protect water resources and improve aquatic and riparian ecosystems and identifying where knowledge gaps exist will improve the ability of the landscape to adapt to change.

Reduced Vegetation Productivity

Impact Scenario

Although the projected climate change impacts of increasing temperature and carbon dioxide on vegetation are complex and uncertain (Schwinning et al. 2008; Reeves et al. 2014), shifts in precipitation patterns and drought intensity will increase plant stress and/or mortality and diminish plant productivity and cover (Breshears et al. 2005; Schwinning et al. 2008; Reeves et al. 2014). Loss of vegetation productivity subsequently reduces forage resources for herbivores and habitat quality for all species, including livestock. These impacts also contribute to community composition shifts, species and ecosystem stress, and species mortality.

Vegetation productivity is not only influenced by climatic conditions, but also by herbivory, soil and microbial characteristics, ecological community composition, and disturbances from wildfire and land use (as reviewed by Milton et al. 1994, Field et al. 1995). For example, because domestic and wild animals select palatable species at certain growth stages, plant establishment may be limited (Milton et al. 1994), especially during times of limited productivity (Schwinning et al. 2008). High intensity grazing in low productivity, drought-stricken areas can lead to shifts in biological community composition (Milchunas & Lauenroth 1993; Harris et al. 2003; Loeser et al. 2007) or invasive species spread (Loeser et al. 2007).

Under climate change projections, the risk of substantial livestock grazing impacts on vegetation will increase, particularly in areas of lower productivity. Competition between livestock and native herbivores such as mule deer (*Odocoileus hemionus*) and pronghorn (*Antilocapra americana*) will also increase. Times of increased drought and low vegetation productivity have sometimes forced ranchers to supplement feed with external forage resources (Coles & Scott 2009; Nania et al. 2014). In some areas of the Southwest, non-native, invasive Lehmann lovegrass (*Eragrostis lehmanniana*) has been introduced as a supplement to forage resources during drought periods (Archer & Predick 2008; U.S. Forest Service 2012). However, non-native and highly invasive species like Lehmann lovegrass threaten native species and reduce the adaptive capacity of the landscape over the long-term. Research has identified other native species that are less sensitive to climate change and non-native species invasions and can be used for restoration efforts (U.S. Forest Service 2013; Bernstein et al. 2014). Ongoing research on the North Rim lands is also aimed toward identifying which native species and genotypes are likely to establish most effectively under changing climate conditions (see www.grandcanyontrust.org).

Recommended Adaptation Actions

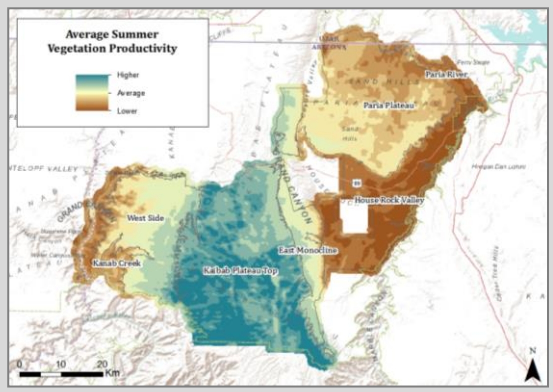
Support agency and ranching partners in ongoing monitoring of vegetation productivity and forage utilization indicators. Use forage and vegetation monitoring to guide livestock management decisions to protect against overgrazing. As the risk of livestock grazing impacts may increase in areas with limited vegetation productivity, we should support agency and ranching partners in the monitoring of vegetation productivity and forage utilization indicators. For example, on-the-ground monitoring efforts can be coupled with other ecological assessments to reduce resource burdens.

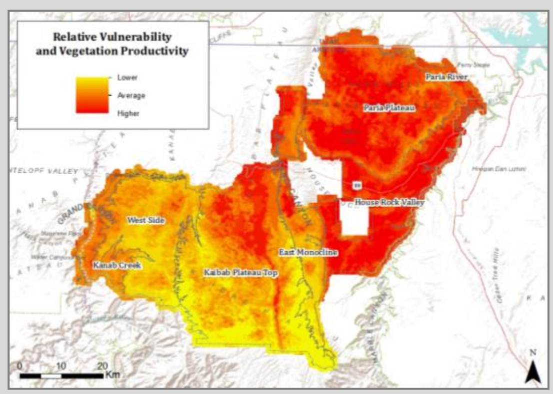
Remotely-sensed data, such as from Normalized Difference Vegetation Index (NDVI), can provide near-real time information on drought and related vegetation productivity impacts (e.g., Vose et al. 2015; see *Data Resources* sidebar in this section). NDVI is an index of vegetation primary productivity that serves as an indicator of ecological responses to environmental change, including climate change (Pettorelli et al. 2005; Breshears et al. 2005; Loew et al. 2008). This information can provide input into "early warning systems," such as the Livestock Early Warning System (Stuth 2015), which gauge the impacts of emerging weather events on forage supply and may have potential to be employed across the North Rim Ranches.

Rotational grazing patterns rely on grazing opportunities in the upper elevations of the Kaibab Plateau during the summer when vegetation is relatively more productive compared to other grazed geographic areas. These patterns shift in the winter to the Paria Plateau and House Rock Valley when conditions are reversed. We should link rotational grazing strategies with monitoring information such that we manage livestock to reduce grazing pressure in lower productivity areas to reduce climate vulnerability on the North Rim lands.

DATA RESOURCES

NDVI is a remotely-sensed metric of vegetation greenness that is used to represent vegetation productivity. In the figure to the right, we calculated an 11-year average of summer (June-August) NDVI* (top). The Kaibab Plateau and East Monocline have the highest vegetation productivity relative to the rest of the landscape. Vegetation productivity can be overlaid with our landscape-scale estimate of climate vulnerability (bottom). Based on this overlay, House Rock Valley and the Paria Plateau have the highest vulnerability (relative to other areas of the North Rim Ranches) with respect to the impact scenario of reduced vegetation productivity whereas the West Side and Kaibab Plateau have the lowest relative vulnerability.





* Additional Notes: To estimate average summer vegetation productivity methods, we used remotely-sensed Moderate Resolution Imaging Spectroradiometer NDVI data (MODIS; National Aeronautics and Space Administration; www.lpdaac.usgs.gov/products/modis_products_table/mod13q1data) from the earliest data possible (2000) to 2010. We selected 1-5 images to represent each year within the June-August summer season depending on the availability of quality images. We averaged NDVI for the 11-year period. NDVI typically ranges from -1 to 1 but is an index and is therefore unitless.

Collaborate with land managers to monitor the impacts of changing vegetation productivity on native wildlife species. Link monitoring information with livestock management decisions and triggers for restoration action. Areas of reduced vegetation productivity may increase competition for forage resources between livestock and native wildlife. Information obtained from agency monitoring of wildlife populations and/or habitat can provide information about areas to target for reduction of livestock grazing pressures or where to focus habitat restoration efforts. Focal species for this type of monitoring should be identified in collaboration with land managers and could include pronghorn, which have been identified as conservation targets in the House Rock Valley and East Monocline geographic areas (Albano et al. 2008), and/or mule deer, which have been the focus of past habitat restoration treatments on the Kaibab Plateau's West Side (Sisk et al. 2010). Ongoing research within the RSP, such as Northern Arizona University's mule deer seasonal distribution modeling and the University of Arizona's mule deer diet quality analyses, can also illuminate wildlife impacts related to drought and vegetation productivity impacts (see www.grandcanyontrust.org).

Explore the development of grassbanks as a method of alleviating grazing stresses during times of extreme drought. We should explore the feasibility of developing grassbanks, or areas of natural grassland that are reserved for the benefit of wildlife and/or used as a safety net during periods of extreme drought (Gripne 2005; Coppock 2011; Straube & Belton 2012).

Community Composition Shifts and Species Loss

Impact Scenario

Climate can directly amplify stresses and mortality risks for species. In response, species may be able to alter their behaviors or may disperse to new suitable habitat by spreading seeds, increasing their home range, moving to a new location, or other means (Glick et al. 2011; Finch 2012). Over a longer term, species may be able to change individual physiology or evolve to adapt to new conditions (Glick et al. 2011; Finch 2012), although such adaptations are likely beyond management-relevant time scales. The success of these adaptations depends on the rate of changing conditions, the availability of new suitable habitat, and barriers to dispersal, among other factors. Species that are considered rare or threatened may be more sensitive to climate changes and, similarly, ecosystems that are already degraded may be more sensitive to impacts and less likely to be able to adapt to climate shifts (Thomas et al. 2004).

As species shift or are lost within an ecosystem, community composition will also change. Shifts in species and community composition across the southern Colorado Plateau will lead to undetermined levels of plant redistribution (Garfin et al. 2010) as species respond differently to shifts in climate depending on their vulnerability to change. In general, species distributions are anticipated to shift upward in elevation and narrow in range (Hughson et al. 2011). Over recent decades, increases in mean annual temperature combined with decreases in mean annual rainfall have already led to shifts in montane vegetation and species habitats in southern Arizona's Santa Catalina Mountains (Brusca et al. 2013). Such shifts are projected to increase with ongoing climate change (Hereford et al. 2002).

By 2090, about half of the western United States is projected to have shifted to climates that are unlikely to support current vegetation (Rehfeldt et al. 2006). Recent projections of vegetation for the Colorado Plateau for 2045-2060 also show considerable changes from present distributions (U.S. Bureau of Land Management 2012). Grasslands may contract with climate change-driven drought as overall grass cover is positively related with average annual precipitation (Gremer et al. 2015). However, C3 (cool season) and C4 (warm season) grasses respond differently to climatic signals: C3 grass cover is more negatively impacted by an increasing temperature range while C4 grass cover is more negatively impacted by variability in the seasonality and timing of precipitation (Gremer et al. 2015). Woody shrub expansion into grassland ecosystems due to fire exclusion can also result in loss of C4-dominated grasslands – once woody shrubs are established, populations continue to spread regardless of future fire frequencies (Briggs et al. 2005). Tree encroachment can be encouraged by livestock grazing through reduction of understory grasses that lessen competition for other seedlings (Belsky & Blumenthal 1997). The USFS has already identified ongoing tree encroachment into the montane/subalpine grasslands on the Kaibab Plateau as a specific concern (Albano et al. 2008; U.S. Forest Service 2014b). These Kaibab Plateau grasslands have been historically impacted due to fire exclusion-influenced nutrient limitations and conifer encroachment, resulting in a loss of overall grassland abundance.

Loss of sagebrush shrublands and grasslands is also of concern as declines in sagebrush steppe (sagebrush [*Artemesia* spp.], saltbrush [*Atriplex* spp.]) are projected (Munson et al. 2011). Sagebrush species distributions may move northward and experience an overall decline (Shafer et al. 2001, Bradley 2010) while other shrub species such as Gambel oak (*Quercus gambelii*), may expand their distribution with projected climate changes (Rehfeldt et al. 2006; Munson et al. 2011). Pinyon-juniper woodlands have the potential encroach on the sagebrush grasslands of the West Side and the Paria Plateau, suppressing understory growth and risking soil erosion (Albano et al. 2008). However, the future distribution of pinyon-juniper woodlands is unclear as species-specific distributions do not necessarily align with community type projections (Rehfeldt et al. 2006). Some species-specific projections suggest an increase in juniper species and juniper-dominated woodlands (Munson et al. 2011) while others suggest an overall reduction and a lateral geographic shift in juniper distribution by 2090, away from current distributions in northern Arizona and Utah (Rehfeldt et al. 2006). Other projections suggest an ongoing decline of seed cone production for pinyon pine with increasing temperatures, subsequently reducing pinyon pine regeneration (Redmond et al. 2012). These various projected shifts may point toward a significant decline in the co-occurrence of pinyon and juniper (Rehfeldt et al. 2006).

Decreases in some forest and woodland types are also projected with climate change (U.S. Bureau of Land Management 2012; Vose et al. 2015). Increased aridity may lead to increased tree mortality in some areas of the Colorado Plateau (Munson et al. 2011; U.S. Bureau of Land Management 2012) and, within ponderosa pine and Douglas-fir communities, the dominant tree species are projected to have reduced distributions (Rehfeldt et al. 2006). Forest ecosystems will also be transformed through changing wildfire regimes (Dale et al. 2001; Williams et al. 2010), as described in *Increased Risk of Unnaturally Severe Wildfires* below.

Recommended Adaptation Actions

Support and coordinate with land managers to implement climate-focused forest management. We should support land managers in the restoration of ponderosa pine, pinyon-juniper, and mixed-conifer forests where non-climate drivers of community composition shifts such as biodiversity loss, invasive species, and unnaturally severe wildfires are prevalent. We make specific recommendations for invasive species- and wildfire-related adaptation action in the respective impact scenario sections below. Forest treatments to increase understory diversity and to reduce wildfire risk are critical and we should endeavor to maintain structural diversity and to limit the competition for resources that can result from even-aged stands (Albano et al. 2008).

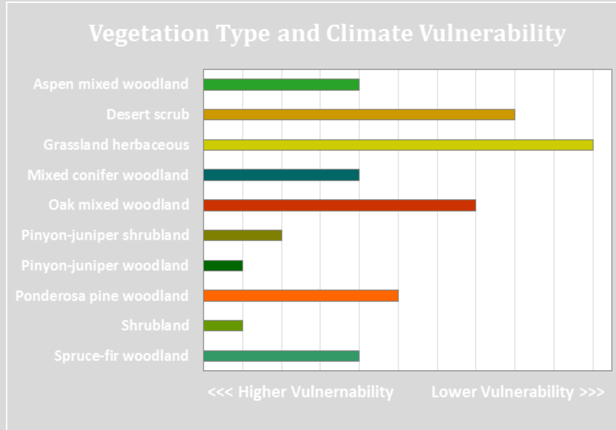
Develop and implement native grassland restoration plans in collaboration with land managers. We should encourage and pursue the restoration of native grasslands in areas where non-climate drivers such as invasive species and wildfire are prevalent. Restoration efforts can be informed by the Restoration Plan (Albano et al. 2008), the Applied Research Plan (Grand Canyon Trust et al. 2011), and other research on the North Rim lands. Recent research on grassland restoration in House Rock Valley has provided important lessons on the ecological tradeoffs between successful seeding techniques and soil disturbance (Bernstein et al. 2014). While successful native grass establishment was achieved using drill-seeding within a specific climate window (simulated wet winters), related soil disturbance increased invasive species germination and erosion risk (Bernstein et al. 2014). Although arid grasslands are some of the most difficult areas in which to restore native vegetation (Nania et al. 2014; Bernstein et al. 2014), ongoing restoration research projects on North Rim Ranches are working to identify native grass species and seeding techniques that can outcompete cheatgrass post-disturbance as well as native species genotypes that are more drought-tolerant in a changing climate (see www.grandcanyontrust.org).

Continue to monitor indicators of species and community diversity. Link assessments of landscape-scale climate vulnerability and triggers for protection and restoration. Land management that optimizes native species diversity can support ecosystem- and landscape-scale adaptive capacity for climate change. For example, forest management actions that favor or plant a mixture of drought-tolerant species and genotypes can accommodate uncertainty related to forest stand-level drought vulnerability and reduce impacts from pest and disease outbreaks (Vose et al. 2015). During 1997-2008, about 7.6% of forests across the Southwest were devastated due to bark beetles (*Ips* spp.; A. P. Williams et al. 2010); vulnerability to disease or pest outbreaks is projected to increase over the 21st century. Increasing pest and disease outbreaks are a concern highlighted in the Kaibab National Forest's Land and Resource Management Plan (U.S. Forest Service 2014a).

We should continue to support monitoring species- and community-level diversity, co-locate monitoring efforts at Baseline Assessment points, and use site-specific data where possible, including remotely-sensed vegetation data (see *Data Resources* sidebar in this section). Monitoring thresholds associated with declines in diversity can help guide livestock grazing or other land uses away from drought-stricken areas where additional stresses can lead to shifts in community composition (Milchunas & Lauenroth 1993; Harris et al. 2003; Loeser et al. 2007).

DATA RESOURCES

Vegetation type data* can be used to determine community diversity and transition areas. In the figure to the right, we estimate the relative climate vulnerability value that overlaps the majority of each vegetation type (excluding "barren"). Shrubland and pinyon-juniper shrubland and woodland have relatively higher vulnerability than other types.



* Additional Notes: Northern Arizona University developed dominant vegetation type model specifically for the North Rim Ranches to improve upon the local accuracy of other remotely-sensed vegetation type layers such as the 2004 Southwest ReGap (U.S. Geological Survey Gap Analysis Program; swregap.nmsu.edu) and 2010 LANDFIRE (LANDFIRE; www.landfire.gov) layers. To develop the vegetation data layer, the model was "trained" using vegetation data collected at Baseline Assessment points, confirmed with aerial imagery, processed using a decision-tree algorithm, and evaluated for accuracy (over 90%).

Increased Risk of Invasive Species Spread

Impact Scenario

Invasive species outcompete native species, threaten habitat quality, and predispose an ecosystem to impacts from additional disturbances like climate change. For example, climate change-driven increases in summer precipitation variability can cause direct mortality in shallow-rooted species in dry years. When coupled with nonnative species invasions such as tumbleweed (*Salsola* spp.), cheatgrass (Schwinning et al. 2004), Lehmann lovegrass (U.S. Forest Service 2012), or red brome (*Bromus madritensis rubens;* Bureau of Land Management 2012), dramatic species community shifts will occur. As minimum temperatures are a primary driver of species' ranges (Inouye 2000), milder winters on the Kaibab Plateau have the potential to encourage invasive species to move up into higher elevations. Invasive grasses such as red brome and cheatgrass have already expanded into low- and mid-elevation woodlands and shrublands across the Intermountain West, particularly in areas with relatively low existing perennial grass and forb cover (Chambers & Pellant 2008).

Invasive cheatgrass is of particular concern on the North Rim Ranches, particularly on the Kaibab Plateau's West Side (U.S. Forest Service 2014a) as it can increase wildfire risk through fine fuels buildup, outcompete more palatable species, reduce forage for livestock, and increase overall climate vulnerability Model results show both positive and negative growth and spread rates for cheatgrass under projected climate change (Bradley et al. 2009). The distribution of cheatgrass may shift northward or higher in elevation, reducing its presence in some areas and increasing its presence in others (Finch 2012). However, where cheatgrass distribution contracts, other invasive grass species like red brome are anticipated to expand (Archer & Predick 2008; Hughson et al. 2011), continuing the fire-invasive grass positive feedback cycle that degrades landscapes (Finch 2012). With these projections, geographic areas of the North Rim lands with substantial cheatgrass infestations (i.e., the West Side) can be expected to have little respite from the stress of invasive species and the related wildfire feedback cycle.

The influence of livestock grazing on cheatgrass spread shows mixed results. Some studies have made links between livestock grazing and cheatgrass invasion through livestock impacts to biological soil crusts. Trampling by livestock reduces the integrity of biological soil crusts which subsequently increases erosion, reduces productivity, and increases the vulnerability of an ecosystem to cheatgrass spread (Stein Foster et al. 2010; Reisner et al. 2013). Other studies have documented that strategic livestock grazing can reduce understory fuel loads (Belsky & Blumenthal 1997) including cheatgrass (Schmelzer 2009), but that overall impacts to fuel loads are dependent on weather and vegetation conditions (Strand et al. 2014). When coupled with targeted prescribed burning, strategic grazing can be more effective at reducing cheatgrass than with burning or strategic grazing alone (Diamond et al. 2012). Still other studies suggest that some grazing intensities can increase native biodiversity while others increase cheatgrass abundance (Loeser et al. 2007). Therefore, decisions about whether or not to graze livestock in cheatgrass-invaded areas should be tailored to site-specific information (e.g., weather, vegetation condition, soil health) that can weigh fuel load reduction opportunities against the risk of cheatgrass spread and loss of biological soil crusts. Ongoing research on the North Rim Ranches is evaluating the relationship between wildfire, livestock grazing, and restoration techniques on cheatgrass spread (see www.grandcanyontrust.org). However, North Rim Ranches' pastures that are heavily invaded by cheatgrass (e.g., the West Side) are not grazed by livestock to reduce the risk of cheatgrass spread.

Tamarisk and Russian olive (*Elaeagnus angustifolia*) are other invasive species of particular concern. These species reduce water flow, outcompete native species in riparian areas, alter wildfire frequency, and contribute to habitat conversion and loss of habitat quality (as reviewed by Hultine et al. 2010). USFS and BLM have highlighted these invasive species as management targets. Specific to tamarisk, these land management agencies have outlined objectives to monitor the ongoing influence of the recently introduced tamarisk beetle (which defoliates tamarisk), to reduce tamarisk abundance through specific management actions, and to pursue native cottonwood (*Populus* spp.) and willow (*Salix* spp.) habitat restoration (U.S. Bureau of Land Management 2008a, 2008b; U.S. Forest Service 2014a). While the distribution of tamarisk may not be impacted directly by climate change, severe droughts coupled with increased risk of unnaturally severe wildfire may accelerate tamarisk invasions since this species is quicker to rebound than native cottonwood and willow species (Finch 2012). Tamarisk also contributes to wildfire risk and poses a particular threat to riparian ecosystems which are not fire-adapted, creating another fire-invasive species feedback cycle (Finch 2012). Along the Paria River and Kanab Creek, and in washes and at springs in House Rock Valley, the threat of tamarisk outcompeting native riparian habitat is expected to continue.

Recommended Adaptation Actions

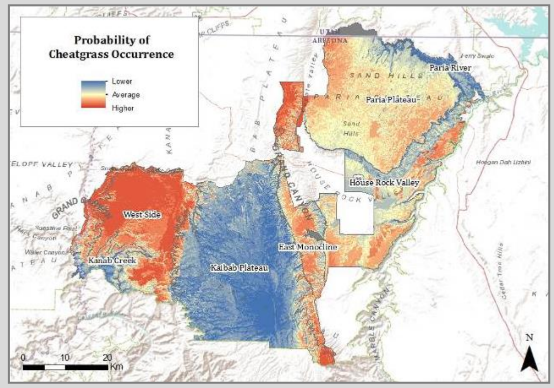
Work with land managers to continue and/or increase invasive species abatement in climate-vulnerable areas, with particular emphasis on invasive cheatgrass and tamarisk. Invasive species such as cheatgrass pose significant threats to native biodiversity and natural wildfire regimes, particularly in an increasingly warmer climate with amplified precipitation variability. We should continue to support land managers' efforts to mitigate invasive species spread and to promote native species restoration. While some practices advocate restoration seeding with non-native species to achieve provide short-term cover objectives, long-term management issues with non-native species (e.g., McMaster et al. 2015) emphasize the need to prioritize and use native seeds and drought-tolerant genotypes in restoration efforts (Wood et al. 2015).

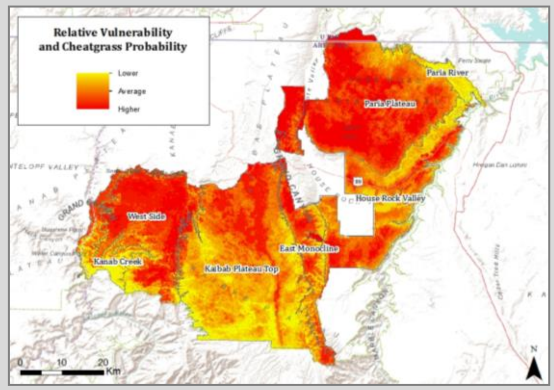
Invasive species removal has been a predominant focus of wildlife habitat and riparian ecosystem restoration and should continue to be at the forefront of these efforts. The Trust has led restoration efforts to remove tamarisk and Russian olive along the Paria River and to remove tamarisk and other invasive grasses and forbs at riparian areas in House Rock Valley. Ongoing monitoring of the results of these efforts will be critical for informing approaches that can be applied to other areas across the North Rim lands.

Collaborate with agency and research partners to map and monitor invasive plant species populations. We should track the status of native and non-native species abundance and diversity indicators over long-term (e.g., 5-15 year cycles), following the lead of the Baseline Assessment. Disturbed areas, such as areas burned by wildfire, should be a primary focus as these can be sites more vulnerable to invasion. Information from such monitoring efforts is critical for gauging disturbance impacts, assessing climate vulnerability, and triggering restoration and adaptation action (e.g., invasive removal and native plant reintroduction). Past research has modeled the probability of cheatgrass spread across the North Rim lands, providing information of at-risk areas (see *Data Resources* sidebar this section; Sisk et al. 2010). Invasive species mitigation and native plant restoration work should be coupled with monitoring of abundance and diversity indicators to gauge effectiveness or to trigger additional action.

DATA RESOURCES

The Baseline Assessment provides a wealth of species data, including invasive species presence. Using these data, research partners modeled the probability of cheatgrass occurrence across the North Rim Ranches (top figure adapted from Sisk et al. [2010]). Models of invasive species distributions such as this cheatgrass model can be overlaid with our landscape-scale estimate of climate vulnerability to help inform restoration actions. Our overlay of cheatgrass probability with climate vulnerability (bottom) showed the West Side and the Paria Plateau to have the highest vulnerability (relative to other areas of the North Rim Ranches landscape) in terms of the impact scenario of climate change-driven invasive species risk.





Minimize land-use disturbances, such as recreation, roadways, and livestock grazing in heavily invaded areas. We should continue to work with land managers to reduce compounding disturbances from recreation and roadways, especially in heavily invaded areas. We should continue to manage livestock using rotational grazing strategies that include closed or restricted pastures to protect reference and restoration areas (Albano et al. 2008) and, where necessary, set aside new reference and restoration areas (Straube & Belton 2012).

Continue to build knowledge and use best-available science of mechanisms of invasive species spread, optimal techniques for native plant restoration, and opportunities for mitigation efforts. Employing best-available science and on-the-ground experience is critical for successful adaptation action with respect to invasive species. We should use research results that can improve our understanding of mechanisms of invasive species spread, optimal techniques for native plant restoration, and opportunities for mitigation efforts. For example, tamarisk cover can be substantially reduced over the long-term through cutting and burning methods; but, successful restoration must be coupled with native plant reestablishment efforts as species in these areas may not be quick to respond to reduced competition (Harms & Hiebert 2006).

Invasive species management is a primary research focus for the RSP as detailed in the Applied Research Plan (Grand Canyon Trust et al. 2011). For example, ongoing research is evaluating the efficacy of native plant "greenstrip" fuelbreaks to reduce the spread of invasive cheatgrass and how success is influenced by seeding techniques, wildfire, and livestock grazing (see www.grandcanyontrust.org). Other innovative research modeling fire connectivity based on cheatgrass fuels can be used to identify locations where these native plant fuelbreaks in the cheatgrass-invaded West Side can be planted to interrupt fire connectivity (Gray & Dickson 2016).

Increased Risk of Unnaturally Severe Wildfires

Impact Scenario

Forest growth and mortality in the Southwest and Colorado Plateau are vulnerable to increasing temperatures, drought, and increased risk of unnaturally severe wildfires. Historical fire weather patterns in the Southwest have shown that fire risk correlates directly with warming and earlier spring snowmelt (Westerling et al. 2006). Despite wet winters, annual area burned rose in the late 20th century. This is likely due to summer drought and greater accumulation of fine fuels from wet winters and coarse fuels due to fire suppression (Swetnam and Betancourt 1997). Both fire frequency and fire severity are projected to increase dramatically with climate change and related precipitation variability (Garfin et al. 2013) as increased plant mortality contributes to a buildup of fine fuels (Chambers & Pellant 2008). In addition to increasing forest mortality, wildfire can also impact the regeneration of ponderosa pine forests (Williams et al. 2010) and reduce carbon storage while increasing agency fire management costs (U.S. Forest Service 2014a). Increasing wildfire risk is particularly problematic in forests dominated by pinyon pine, ponderosa pine, and Douglas-fir (Williams et al. 2010), which are the common forest types across the North Rim lands. The greatest impacts are projected for dense stands where fuel loads are high (Williams et al. 2010).

Increased risk of unnaturally severe fire is already a substantial concern on the Kaibab National Forest where historical fire suppression and invasive cheatgrass provide prime conditions for increased wildfire severity. The 2014 Kaibab National Forest Plan (U.S. Forest Service 2014a) identifies wildfire as a climate change concern. Stand-replacing fires in ponderosa pine and mixed conifer communities can result in substantial soil loss and related soil productivity loss, flooding, and damage to water diversions and other improvements, displacement of native understory species by non-native, invasive species, limited recovery of desired tree species and stand structure, and uncharacteristically high accumulations of large fuels in frequent fire systems (U.S. Forest Service 2014b).

Invasive grasses such as cheatgrass respond rapidly after wildfire disturbance and contribute to a buildup of fine fuels, shifting fire regimes and increasing fire frequency (Chambers & Pellant 2008). Shifts in fire regimes, especially when coupled with non-native species invasions, can contribute to vegetation community conversions and declines in overall forest health (Westerling et al. 2006). Across the North Rim lands where cheatgrass is present (e.g., the West Side), there is substantial concern about the risk of large wildfires due to the cheatgrass-wildfire feedback cycle. Increasing risk of unnaturally severe wildfire subsequently increases the risk of cheatgrass spread, and vice versa, reducing overall ecosystem health through altered fire regimes and trends toward monoculture.

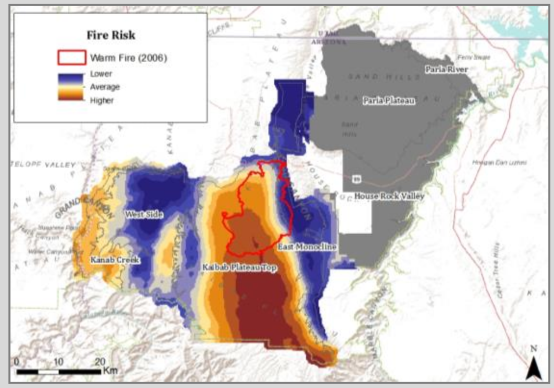
Recommended Adaptation Actions

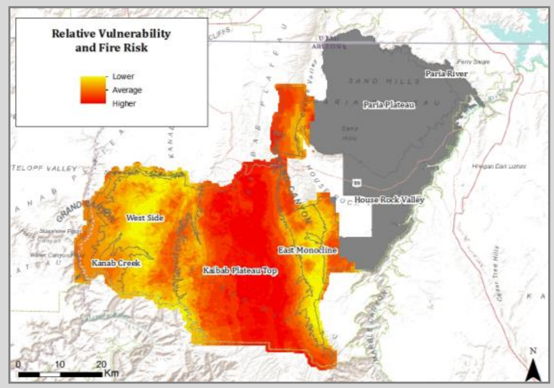
Work with agency, ranching, and research partners to identify and implement fire management treatments that reduce the threat of unnaturally severe wildfire and allow low- to mixed-severity fire to drive adaptation trajectories. We should continue to work with partners to engage in forest management practices that reduce the threat of unnaturally severe wildfire but allow for low- to mixed-severity wildfire. Proactive wildfire risk assessment and treatments can identify and target high-risk areas such as the West Side. This work includes supporting land managers in climate-focused fire and forest management ranging from mitigating human-caused wildfire ignitions, which account for 25% of wildfire on the Kaibab National Forest (U.S. Forest Service 2016), to proactively managing the landscape to reduce fuel loads and maintain ecosystem health.

The Trust has worked with Northern Arizona University to model fire risk and fire hazard for the Kaibab Plateau geographic area (see *Data Resources* sidebar in this section). Other datasets and tools such as LANDFIRE (LANDFIRE; www.landfire.gov) and FlamMap (FlamMap; www.firelab.org/project/flammap) could be explored as resources for additional fire risk modeling. This information can be overlapped with models of landscape-scale climate vulnerability to help prioritize on-the-ground adaptation action. Recent modeling of fire connectivity based on cheatgrass fuels for the West Side of the Kaibab Plateau can also identify priority locations for adaptation action (e.g., native plant fuelbreaks) can reduce unnaturally severe wildfire (Gray & Dickson 2016). This adaptation action recommendation echoes those made for the invasive species, community composition shifts, and vegetation productivity impact concerns as promoting native plant establishment and limiting invasive species spread can limit fine fuel accumulation.

DATA RESOURCES

Following the Baseline Assessment, research partners modeled fire risk* for the western North Rim Ranches based on 1986-2005 fire data (top). Although this model does not include more recent data, including the 40,000-acre Warm Fire (2006), it can be useful in the characterization of the unnaturally severe wildfire risk. Higher fire risk across the Kaibab Plateau and Kanab Creek highlight adaptation action priorities. Fire risk for the western North Rim Ranches can also be overlaid with our landscape-scale estimate of climate vulnerability (bottom). Based on this overlay, the Kaibab Plateau has the highest vulnerability (relative to other areas of the North Rim Ranches) in terms of climate-driven risk of unnaturally severe wildfire.





* Additional Notes: Northern Arizona University developed this fire risk data as a predictor of the probability of large fire burning over a 20-year period. Using weights-of evidence modeling approach, fire data were obtained from the Program for Climate, Ecosystem, and Fire Applications (Desert Research Institute; www.cefa.dri.edu) for 1986-2005 and modeled as a function of topography, dominant vegetation type, and mean annual precipitation. Topographically rough areas in ponderosa pine-dominated forest on south-facing slopes at moderate elevations were found to be the best predictors of fire occurrence.

Work with land managers to restore historical fire regimes to fire-adapted ecosystems such as ponderosa pine forests and pinyon-juniper woodlands. Restoration of southwestern ponderosa pine forests to historical fire regimes is considered urgent as decades of livestock grazing, logging, and wildfire suppression have increased the risk of unnaturally severe fires that threaten human and ecological communities (Allen et al. 2002). In this context, the USFS recommends thinning and prescribed burning as management strategies for maintaining desired habitats in the face of climate change (U.S. Forest Service 2014a).

We should work with land managers to pursue fire management that encourages development and maintenance of desired vegetation communities and habitat characteristics while minimizing the establishment of non-native, invasive species (Albano et al. 2008). Past work within the Kaibab Forest Health Focus – a science-based, collaborative effort to guide landscape-level forest restoration efforts – made recommendations for forest restoration treatments and management actions including wildfire and climate considerations (Sisk et al. 2009). Related research has modeled the effects of forest treatment scenarios on focal species such as the northern goshawk

(*Accipiter gentilis*), identifying that unnaturally severe wildfire can nearly double reductions in species occurrence as compared to proactive forest treatments (Ray et al. 2014).

Work with land managers to apply post-fire restoration seeding treatments that utilize native species and incorporate climate-resilient plant genotypes. We should support practices that promote native species restoration (Wood et al. 2015) and reduce opportunities for invasive establishment after fires. These practices could include avoidance of seeding with non-native grasses (McMaster et al. 2015) and protection against other post-fire landscape stresses, such as introducing livestock grazing too soon after fire (Mork 2010). We should continue to monitor post-fire vegetation indicators that represent understory regeneration and the impacts of herbivory post-fire from livestock grazing, particularly in the footprint of the 2006 Warm Fire (McMaster et al. 2010; Mork 2010).

Reduced Landscape Connectivity

Impact Scenario

Landscape intactness is an important component of climate adaptation as demonstrated in our climate vulnerability assessment, and the relative naturalness of the North Rim lands provide important ecosystem linkages between the public lands of the southern Colorado Plateau. Habitat connectivity is critical for species' abilities to adapt to projected climate changes through dispersal as well as for facilitating species migration and gene flow (Heller & Zavaleta 2009; Glick et al. 2011; Finch 2012). However, as species and ecosystems shift with climate change, protected corridors and other movement pathways will undergo changes as well (Beier 2012; Nuñez et al. 2013). Just as habitat loss can occur through loss of water resources, unnaturally severe wildfires, invasive species spread, or shifting community composition, connectivity, too, is affected by these climate-driven disturbances.

Population growth and increased socioeconomic demand can couple with climate change to put additional stresses on water, forests, and other resources. Fortunately, the North Rim lands have low population densities at present, and the USFS projects low residential development on adjacent private lands into the future compared to other national forests (Susan et al. 2007). However, models of near-term future landscape intactness at the scale of the Colorado Plateau project declines in ecoregional connectivity by 2025 due to fragmentation from projected energy (oil, gas, mineral, and renewable) development; agricultural (including livestock grazing) influences; urban, road, and recreational development; and invasive species (U.S. Bureau of Land Management 2012). Threats to landscape intactness at the scale of the Colorado Plateau emphasize the importance of maintaining the large blocks of intact land across the landscape of the North Rim Ranches to promote habitat connectivity in the region.

While the North Rim lands exhibit high landscape intactness at the scale of the Colorado Plateau, road and fence infrastructure within the North Rim Ranches can act as animal movement barriers. For example, some fences in House Rock Valley have been identified as limiting habitat quality for pronghorn as the design of the bottom wire (barbed, close to the ground) does not allow for pronghorn to pass (Arizona Game and Fish Department 2011). Moreover, the Kaibab National Forest has the highest (dirt and paved) road density on North Rim lands. While the direct impact of these roads on habitat connectivity has not been studied, roads can be vectors for invasive species spread and wildfire ignitions (U.S. Forest Service 2016). While current risk may be low (Susan et al. 2007), future increases in development and recreation in the southern Colorado Plateau will add pressure to expand existing transportation networks and increase habitat fragmentation.

Habitat connectivity is scale- and species-dependent and movement pathways may be difficult to identify, presenting a substantial challenge for identifying target areas for adaptation action. However, existing modeling and ongoing monitoring efforts at both the Colorado Plateau- and North Rim Ranches-scales provide information on occupancy and connectivity for a suite of focal species (including mule deer and mountain lion [*Puma concolor*]) that can inform where adaptation action can take place (see www.grandcanyontrust.org). Focusing on protecting water resources can also support landscape connectivity and adaptive capacity. Riparian corridors are natural pathways for animals and plants (Beier 2012) and riparian ecosystems across North Rim lands, particularly low-elevation springs, connect habitats, especially for wider-ranging animals.

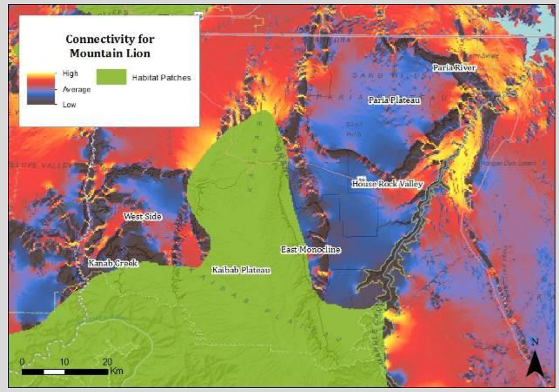
Recommended Adaptation Actions

Work with agency, ranching, and research partners to plan and implement actions that protect and/or restore landscape connectivity across the North Rim Ranches, particularly for focal species. The Trust has worked with research partners from Northern Arizona University and Conservation Science Partners, Inc. to model landscape connectivity for a suite of focal species on the Colorado Plateau, including mountain lion and pronghorn (see *Data Resources* sidebar in this section). When linked up with spatial information on invasive species or water resource availability, these models can identify where animal movement is restricted or deterred to help target adaptation action. Post-restoration monitoring can inform the effectiveness of modification efforts and their likelihood of success at larger scales.

We can work with ranching partners and land managers to modify ranching infrastructure where needed to reduce impacts on landscape connectivity or improve resource protection. In a conservation context, ranching infrastructure such as fencing is a critical component of resource protection (e.g., waters, reference areas) and maintaining rotational grazing patterns. However, we should also address where the extensive fence network related to ranching infrastructure negatively impacts landscape connectivity. Opportunities for improving landscape connectivity can include removal of old and unused fencing within closed or restricted pastures. This work could also include repair of existing fences that protect reference and restoration areas and modifying fences to be more wildlife crossing-friendly, such as in House Rock Valley where fences can restrict pronghorn movement (Arizona Game and Fish Department 2011). For pronghorn, this includes replacing bottom barbed wire strands with barbless wire to allow and raising them to 0.46 m (1.5 ft) to allow animals to crawl under fences (Harrington & Conover 2006). The USFS acknowledges that reducing landscape fragmentation and maximizing landscape connectivity are important management concerns on the Kaibab National Forest, particularly for maintaining pronghorn connectivity (U.S. Forest Service 2014a). Since 2005, the Trust has worked with ranching partners and volunteers to map these fences and modify them to facilitate wildlife movement. We should continue to support related management actions whenever possible.

DATA RESOURCES

Research partners have modeled connectivity for several species on the Colorado Plateau. This can help identify of where animal movement is restricted and inform species-specific vulnerability maps. In the example map to the right, green areas are high quality habitat for mountain lion while yellow and red areas are high concentrations of connectivity (adapted from Dickson et al. 2013).



Work with land managers and other stakeholders to advocate against land-use stresses that can sever connectivity at the Colorado Plateau scale. At the scale of the Colorado Plateau, we should work with agency and other partners to advocate against development that can sever landscape connectivity. Landscape intactness is one of three components in our landscape-scale assessment of climate vulnerability on the North Rim Ranches and areas of lower climate vulnerability may serve as climate refugia for some species. We should collaborate with RSP partners and stakeholders in neighboring landscapes to prevent future fragmentation from roadways or infrastructure development on the Colorado Plateau, including on the North Rim lands. The USFS already identifies collaboration with AGFD and Coconino County (Arizona) as critical in encouraging the protection of open lands and decreasing the potential for future land fragmentation (U.S. Forest Service 2014a). We should formally support these efforts to ensure that the North Rim lands are included in regional assessments.

Protect and restore water resources to enhance landscape connectivity, especially in riparian corridors. Efforts to protect and restore water resources can further support landscape connectivity. We recommend water resource protection and restoration as a primary adaptation action, particularly in areas of the North Rim lands that have low densities of or large distances between water resources. We outline our recommended adaptation actions for water resources in the above *Reduced Water Availability* section.

Increase efforts to mitigate and manage invasive species and unnaturally severe wildfire. Landscape intactness and connectivity can be protected through mitigating invasive species spread and unnaturally severe wildfires, which can substantially shift vegetation communities and alter habitat conditions and connectivity. We outline recommended adaptation actions in the respective scenarios above in *Increased Risk of* Invasive Species Spread and *Increased Risk of Unnaturally Severe Wildfires*.

Increased Livestock Management Challenges

Impact Scenario

Livestock management across the Colorado Plateau and western United States has altered vegetation composition, wildfire regimes, and riparian ecosystem health over the last century or more (Fleischner 1994; Abruzzi 1995). As a conservation organization and the grazing permittee of the North Rim Ranches, the Trust prioritizes appropriately managing the rate, timing, duration, and intensity of livestock grazing to minimize ecological impacts. Over the last decade, the Trust has led efforts to support ecosystem health through this type of conservation-oriented grazing and through science-based management and restoration (Sisk et al. 2010). The Trust has worked with land and livestock managers to reduce stocking rates, employ a rotational grazing arrangement that includes ungrazed reference areas, and modify ranching infrastructure to promote wildlife habitat and habitat connectivity. In addition, the Trust has worked with partners to maintain active research and restoration programs across the North Rim lands that demonstrate the benefits of inclusive, science-based management. Together, these practices fit in well with recommendations from other areas of the Colorado Plateau that promote ecological sustainability, social acceptability, and economic viability (Straube & Belton 2012). These conservation-oriented practices provide a key advantage for addressing climate change on the North Rim Ranches.

Nevertheless, ongoing climate change will impact livestock and ranching livelihoods as changes in forage availability, reduced water resources, and increased exposure to heat stress and disease will affect livestock grazing (Adams et al. 1998; Thornton et al. 2009; Briske et al. 2015). Although sensitivity to heat stress differs among livestock breeds (Thornton et al. 2009; Nania et al. 2014), heat stress typically results in reduced foraging and therefore reduced weight gain, degraded health, or even mortality (Adams et al. 1998; U.S. Climate Change Science Program 2008).

Water limitations can also increase livestock stress (Briske et al. 2015). Reduced water availability, as discussed in *Reduced Water Availability* above, has the potential to increase competition for water resources with wildlife or encourage the development of additional water diversions, such as from natural springs, further stressing ecosystems. The possibility of a reduced water table on the Paria Plateau could affect major springs and groundwater sources which provide winter water for livestock. Livestock can also be impacted by shifts in the amount, quality, and seasonal availability of forage (Briske et al. 2015). As discussed in *Reduced Vegetation Productivity*, reduced vegetation productivity and quality can compound climate-related stresses on livestock and increasing competition with native wildlife.

Of the impact scenarios identified in this adaptation plan, this land use-focused scenario poses a particular challenge as adverse livestock management can compound climate impacts through contributions to soil compaction and reduced infiltration, loss of biological soil crusts, invasive species spread, and vegetation community conversion (Fleischner 1994; Belnap et al. 2009; Harris et al. 2014). Such ecological impacts can subsequently contribute to reduced pasture quality (McPherson and Weltzin 2000; Hulme 2005), further stressing livestock and the landscape. However, negative impacts can be mitigated or avoided by managing livestock to align the duration, seasonality, and intensity of grazing with an area's ecological sustainability and economic viability (Straube and Belton 2012). Conservation-oriented livestock management on the North Rim

Ranches must continue to apply these principles to reduce the risk of compounding climate impacts while also meeting agency and ranching partner goals.

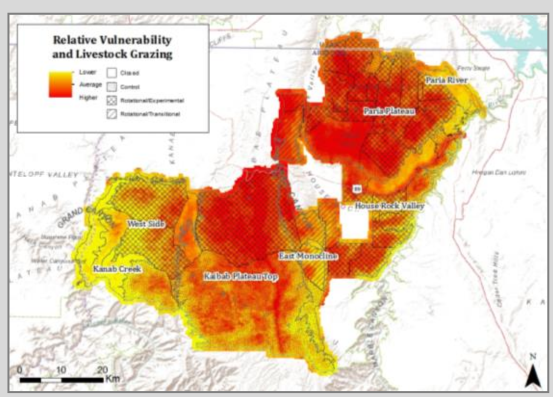
Recommended Adaptation Actions

Work with ranching partners to develop drought risk management. Drought management planning can aid in mitigating drought impacts that may cause additional adverse impacts to production and/or the landscape (Coppock 2011; Briske et al. 2015). We should ensure that livestock management practices consider drought risk and work with ranching partners to plan for intensifying drought periods. Historically, primary strategies for coping with arid, low productivity landscapes have revolved around rotational grazing strategies to reduce stress on vegetation and diversified income strategies to reduce livelihood reliance on livestock grazing alone (Coles & Scott 2009; Coppock 2011). The flexibility of current rotational grazing strategies and the conservative stocking rate on the North Rim Ranches will continue to be critical in addressing land-use stresses. During times of drought risk, maintaining stocking rates that are conservative has been found to result in higher long-term profitability than those that are less conservative (Holechek et al. 1999; Coppock 2011). However, new and creative ways to address potential economic stresses may need to be considered (e.g., Torell et al. 2014).

Continue to maintain flexible, conservation-oriented rotational grazing patterns and stocking rates through an adaptive management framework linked with site-specific monitoring. As drought frequency and intensity are projected to increase with ongoing climate change, rotational grazing should continue to be linked with vegetation productivity and forage utilization monitoring. Maintaining a rotational grazing pattern tied to monitoring data and ecosystem health (see *Data Resources* sidebar in this section) will limit compounding environmental stresses (e.g., invasive cheatgrass) and climate vulnerability. Across the North Rim Ranches, low grazing densities are maintained year-round. Conservative stocking rates and light-to-moderate utilization rates (Holocheck et al. 1999) should continue to be a priority as they reduce the potential for climate change impacts.

DATA RESOURCES

The rotational pasture status as derived from the Restoration Plan (Albano et al. 2008) is depicted in the figure to the right. It includes closed, reference (control), temporary holding (transitional), and rotationally grazed (experimental) areas. Overlaid with the climate vulnerability assessment, this can help inform landscape-scale livestock management as climate change progresses.



Identify tools and practices that support climate-conscious livestock management. Tools and practices that allow for more rapid and effective decisions regarding herd size and pasture rotation will become increasingly important (Coles & Scott 2009). Tools that can provide real-time information about forage availability can support short-term decisions about timing of grazing rotations. These include the Livestock Early Warning System (Stuth 2015) and vegetation green-up information from remotely-sensed up-to-date vegetation productivity metrics (i.e., NDVI). As the climate warms, agency resources such as the Cattle Heat Stress Forecast (U.S. Department of Agriculture Agricultural Research Service; www.ars.usda.gov/Main/docs.htm?docid=21306) can provide real-time information about livestock health risks and perhaps trigger supplemental resource provisions during periods of extreme heat.

Continuing to work closely with ranching partners will identify additional information or tools that can support effective livestock management in a changing climate. In addition, connecting with other conservation-oriented ranchers and organizations across the Colorado Plateau will support knowledge-sharing that can identify and encourage climate adaptation-focused practices.

Continue to integrate appropriate livestock grazing considerations into research efforts. In the Applied Research Plan, monitoring for climate change is specifically linked to sustainable livestock use (Grand Canyon Trust et al. 2011). Livestock grazing is considered by some to be a disturbance that will be exacerbated by climate change while others view grazing as an important management tool in a changing climate (Beschta et al. 2013, 2014; Svejcar et al. 2014). We should continue to support research and monitoring that evaluates livestock grazing impacts in conjunction with invasive species, wildfire, and other disturbances and use findings to inform rotational grazing patterns. There is already substantial discussion about the role of livestock grazing in fine fuels management and wildfire risk reduction and current research on the North Rim Ranches seeks to better understand these relationships (see www.grandcanyontrust.org).

Collaborate with land managers to monitor ecosystem and rangeland health indicators. Future rotational grazing strategies should be tied to monitoring and climate vulnerability and should reflect a diversity in time (duration of grazing use in an area), timing (when an area is grazed), and intensity (Straube & Belton 2012).

Monitoring Recommendations

While we do not provide individual monitoring plans associated with each impact scenario and adaptation action recommended above, we do share general recommendations for monitoring associated with climate adaptation actions. To address Objective 4 in this adaptation plan, we include general monitoring recommendations below.

The Role of Monitoring in Climate Adaptation

Monitoring is an important component of climate adaptation as it provides information on the extent of a stress on a species or ecosystem and can be used to assess the effectiveness of adaptation actions (West et al. 2009; Glick et al. 2011; Briske et al. 2015). A monitoring plan should be directly linked to climate adaptation goals and include measurable indicators of adaptation action success. Monitoring data should be tied to specific adaptation actions, indicate when a threshold or key decision point has been reached and inform the evaluation of action effectiveness (Glick et al. 2011). To build monitoring plans, practitioners recommend developing conceptual maps of the relationships among stresses, ecosystems, and related adaptation actions as an initial step (Busch & Trexler 2003; Margoluis et al. 2009; Conroy et al. 2011). Our scenario-building concept maps in the *Impact Scenario Framework* section above link environmental and land-use stresses with climate impacts and provide a strong foundation for building site-specific monitoring plans. Indicators detect when a stress is impacting an ecosystem, or when an adaptation action is reducing a stress. Each indicator is assigned threshold values that are linked to trigger points or key decisions within the broader adaptive management plan (Busch & Trexler 2003). Because data collected on indicators can also be used in other ecosystem models or decision-support tools, efforts should be made to link data collection efforts among land managers to reduce financial burdens and staff workloads.

To fully realize our climate adaptation objectives, we should seek to develop two types monitoring plans: (1) monitoring plans that track indicators of species, ecosystem, and/or landscape health to gauge when and where climate impacts occur and trigger adaptation decisions and actions; and (2) monitoring plans that track indicators of ecosystem and landscape health to evaluate the effectiveness of adaptation actions and inform management decisions. A range of potential applications exist for monitoring plans that track climate impacts and adaptation efficacy. Many align with our current conservation goals or overlap with existing agency monitoring requirements and present opportunities for science-management partnerships (West et al. 2009). For example, ongoing monitoring of the spread of cheatgrass on the West Side of the Kaibab Plateau provides information for fire risk models and also informs the effectiveness of a recommended adaptation action: restoration of invaded grasslands. While we do not develop climate-related monitoring plans here, the recommendations outlined in this climate change adaptation plan provide a basis for these next steps.

Candidates for Monitoring Indicators

Climate-specific Indicators

In the Applied Research Plan, climate-specific monitoring data were cited as critical for informing livestock management strategies, evaluating the effects of management on wildlife such as pronghorn, predicting cheatgrass spread, and monitoring vegetation conditions and change at a landscape scale (Grand Canyon Trust et al. 2011). Weekly or monthly drought indices as well as longer-term drought trends can be obtained from the U.S. Drought Monitor (The National Drought Mitigation Center; droughtmonitor.unl.edu), the National Center for Environmental Information (www.ncdc.noaa.gov/sotc/drought/201602), and the Arizona Department of Water Resources (Arizona Department of Water Resources Drought Program; www.azwater.gov/AzDWR/StatewidePlanning/Drought/DroughtStatus2.htm). Other real-time climate data is readily available through publicly-available online datasets derived from resources such as PRISM (PRISM Climate Group; prism.oregonstate.edu) or from on-site weather stations such as the Interagency Remote Automatic Weather Stations (National Interagency Fire Center; raws.fam.nwcg.gov) which are present at Four Springs (Paria Plateau), Paria Point (Paria Plateau), Warm Springs Canyon (West Side), and House Rock (House Rock Valley). In addition, two National

Weather Service Cooperative Observer Program (COOP; National Oceanic and Atmospheric Administration; www.nws.noaa.gov/om/coop) stations are present at Jacob Lake (Kaibab Plateau), and Lees Ferry (House Rock Valley/Paria River). Weather stations installed at four Southwest Experimental Garden Array (Southwest Experimental Garden Array; www.sega.nau.edu) sites across the North Rim lands can also provide local climate data. In addition, USFS and BLM monitor precipitation at locations across the landscape to assist with forage utilization and production estimates (U.S. Bureau of Land Management 1991; U.S. Forest Service 2015a). Some of these data are already integrated into livestock grazing decisions while other data can provide additional information related to the extent of climate change exposure and impact risk. When connected to estimations of other metrics, such as vegetation productivity or water resource availability, this information can inform models of climate change impacts to guide adaptation action.

Our climate vulnerability assessment also provides for the integration of data obtained from a variety of sources for long-term monitoring of climate responses and ecological health indicators within an adaptive management framework. For example, the final vulnerability map can be overlaid with spatial representations of other environmental and land-use stresses to help identify restoration and adaptation focal areas. As new data or additional modeling resources become available, updated information can be included in the model to provide more robust projections.

Ecological Indicators

Ecological indicators are commonly used in assessing vulnerability to climate change and prioritizing management actions (Noss 1990, 1999; Cairns et al. 1993; Rapport et al. 1998; Dale et al. 2001). In general, the selection of indicators within a monitoring plan should be scale-dependent and based on sensitivity to stresses, ease of collection and interpretation, and relevance to objectives (Noss 1990; Cairns et al. 1993). At a landscape scale, indicators that represent presence of key ecological components and functioning processes such as connectivity, species distributions, or hydrological flows can be used (Noss 1990; Rapport et al. 1998; Dale et al. 2001). At an ecosystem scale, species diversity and evenness (i.e., relative abundance), the ratio of native-invasive species abundance, or conditions of pre-defined indicator species can serve as indicators (Noss 1990, 1999; Cairns et al. 1993). As no single indicator can meet all criteria for all objectives (Noss 1990; Cairns et al. 1993), a suite of indicators should be used to compile information for climate adaptation decision-making. Below, we make suggestions for indicators that are relevant to each of the seven impact scenarios outlined in this climate change adaptation plan.

Selection of ecological indicators for climate adaptation objectives should also leverage existing monitoring efforts and align with other conservation objectives. The Trust has created a strong foundation for long-term monitoring with its landscape-scale Baseline Assessment, which collected soils and vegetation data at over 600 points across the North Rim Ranches. To guide climate adaptation action, we should continue to support monitoring of ecological indicators at Baseline Assessment points at multi-year intervals as is outlined in the Restoration Plan (Albano et al. 2008) and Applied Research Plan (Grand Canyon Trust et al. 2011). Vegetation metrics derived from indicators monitored in the Baseline Assessment, such as native biodiversity derived from vegetation species surveys, can inform the status of climate-related impacts like species community shifts. Vegetation metrics can also be utilized in models of forage availability that can be linked with livestock grazing rotation decisions (e.g., Stuth 2015), while native and non-native species diversity and abundance can inform invasive species management decisions and efficacy of restoration actions. To further the utility of Baseline Assessment points, subsequent work such as forest overstory assessments and songbird and bat species surveys have been co-located with Baseline Assessment points. Future projects should continue this trend.

Other ecosystem-level indicators have also been collected on the North Rim lands. For example, the Trust has worked with partners to assess spring ecosystem health on select water resources across the landscape, including a subset on the Kaibab Plateau in collaboration with the Springs Stewardship Institute and a subset in Kanab Creek in conjunction with Grand Canyon National Park. As water resources are important for adaptive capacity at ecosystem and landscape scales, continued monitoring of these ecological indicators should be a primary focus.

Monitoring of ecological indicators is also critical for providing feedback on the efficacy of adaptation actions. For example, the Trust is presently monitoring the effectiveness of recent spring ecosystem restoration efforts using indicators derived from herpetofauna, invertebrate, and plant species surveys as well as from large wildlife presence as detected by wildlife camera trapping (see www.grandcanyontrust.org). Monitoring here informs which aspects of springs restoration – invasive species removal, erosion control, or increased wildlife water access – support enhanced aquatic and riparian habitat in an ecosystem impacted by historically intense livestock grazing and associated water diversion. In another example, the Trust has taken on multi-year monitoring of invasive tamarisk and Russian olive presence to determine the effectiveness of invasive species abatement and removal efforts along 13 miles of the Paria River. The results of this monitoring can inform the likelihood of success of applying similar invasive species management approaches in other riparian corridors.

Rangeland Health Indicators

Rangelands are a classification used by land managers to refer to areas that are grazed by livestock. Monitoring indicators of rangeland health not only provide information on landscape and ecosystem conditions but also on the effectiveness of rotational grazing strategies at mitigating the compounding of climate impacts. Indicators of rangeland health can cover soil and site stability, hydrologic function, and biotic integrity (Pyke et al. 2002; Pellant et al. 2005) and include indicators of invasive species, ground and shrub cover, and species composition (Pyke et al. 2002; O'Brien et al. 2003; Pellant et al. 2005; Straube & Belton 2012). Ongoing monitoring of rangeland health is required on the allotments of the North Rim Ranches as outlined in the Allotment Management Plans and is linked to decisions associated with patterns of livestock grazing across the allotments (U.S. Bureau of Land Management 1982, 1983, 1991; U.S. Forest Service 2015a). Some of these requirements include data collection on noxious weeds to assess status and inform treatment options; effectiveness of actions to track progress on conservation objectives for upland vegetation and soil conditions; conditions and trends of species abundance, composition, and ground cover; and soil and watershed conditions to assess water quality and species diversity. USFS identifies the need for annual vegetation or "range readiness" monitoring that assesses status of grasses, forbs, brush, and aspen as indicators of a growing season threshold in which root reserves have been replenished sufficiently to not be impacted by grazing (U.S. Forest Service 2013). In addition, USFS implements annual monitoring of both grazing intensity during the season and forage utilization after the growing season to inform decision-making about plant recovery as part of permit compliance (U.S. Forest Service 2013). Similarly, BLM identifies the need for annual vegetation utilization monitoring that guides decisions on stocking rates. This agency also requires periodic assessments of plant utilization, soil integrity, deviation from plant community potential on its allotments (U.S. Bureau of Land Management 2008b).

We should continue to support USFS and BLM in their rangeland health monitoring efforts. This includes identifying where rangeland health indicators overlap with ecological indicators selected for specific climate adaptation monitoring plans. For example, Baseline Assessment data has the potential to overlap with some of the required monitoring of vegetation and soil characteristics outlined in the Allotment Management Plans and to provide information to support conservation objectives specific to livestock grazing and rangeland health. The Land and Resource Management Plan for the Kaibab National Forest (U.S. Forest Service 2014a) and the Vermilion Cliffs National Monument (U.S. Bureau of Land Management 2008b) and Arizona Strip District (U.S. Bureau of Land Management 2008a) Resource Management Plans each include guides to implementing monitoring and evaluation on managed lands. In these management plans, relevant focal areas include natural waters, soils and watersheds, vegetation communities (e.g., ponderosa pine, grassland), invasive species, wildfire effects on soil and vegetation, wildlife, threatened and endangered species, and livestock grazing, among others.

Summary of Candidate Indicators

CONCERN	FOCAL AREAS	INDICATORS
Drought-impacted water availability	Aquatic and riparian species; natural and livestock waters; riparian corridors	Aquatic and riparian biodiversity; focal aquatic and riparian species abundance (e.g., salt grass; native fish); hydrological flows; seasonal precipitation and drought indices; water resource condition (e.g., seasonality, quality)
Drought-impacted vegetation productivity	Forage resources; livestock production/management; native vegetation communities (e.g., grasslands)	Forage utilization; hydrological flows; native/invasive abundance ratio; seasonal precipitation and drought indices; soil moisture; vegetation green-up and productivity
Community composition shifts	Aquatic and riparian species; native vegetation communities (e.g., grasslands); riparian community vegetation; terrestrial wildlife	Focal species abundance (e.g., sagebrush, mountain lion); focal community distribution (e.g., grasslands); focal riparian species abundance (e.g., salt grass); native/invasive abundance ratio; seasonal temperature indices
Invasive Species Spread	Biological soil crusts, invasive species (e.g., cheatgrass; tamarisk); native vegetation communities (e.g., grasslands); wildfire risk	Biological soil crust abundance; native grass diversity; native/invasive abundance ratio; native riparian vegetation diversity; wildfire history (e.g., ignitions)

CONCERN	FOCAL AREAS	INDICATORS
Increased risk of unnaturally severe wildfire	Invasive species (e.g., cheatgrass; tamarisk); fire-adapted vegetation communities (e.g., pinyon-juniper, ponderosa pine); wildfire risk	Canopy cover; focal fire-adapted community distribution (e.g., pinyon-juniper, ponderosa pine); invasive cheatgrass abundance; seasonal precipitation and drought indices; wildfire history (e.g., ignitions)
Reduced landscape connectivity	Invasive species (e.g., cheatgrass; tamarisk); natural waters; riparian corridors; roadways and infrastructure; wide-ranging terrestrial wildlife (e.g., mountain lion)	Fence condition; focal wide-ranging species presence or movement (e.g., mountain lion); invasive tamarisk abundance; native/invasive abundance ratio; road density; water resource condition (e.g., seasonality, quality)
Increased livestock management challenges	Forage resources; livestock production/management; natural and livestock waters; native vegetation communities (e.g., grasslands)	Forage utilization; livestock production and stocking rate; vegetation green-up and productivity; water resource condition (e.g., seasonality, quality)

Summary of Recommendations

Develop and maintain site-specific monitoring plans that assess climate change impacts and evaluate the effectiveness of adaptation. We should develop and maintain site-specific monitoring plans that assess climate change impact concerns for focal areas that provide information on where and when impacts are occurring. This monitoring should be linked with triggers for adaptation decisions and/or actions, and subsequently evaluate the effectiveness of decisions or actions taken. We should work with land managers and researchers in monitoring efforts and identify opportunities for overlap to reduce resource burdens and increase the utility of data collected. We should select indicators that are relevant to adaptation objectives and, where possible, overlap with agency-directed monitoring plans.

Identify where existing monitoring efforts can support climate impact and adaptation monitoring needs. Since 2005, the Trust has developed a strong foundation for long-term monitoring and has worked with agency and research partners to build information on vegetation, waters, and wildlife across the North Rim lands. We should seek opportunities to utilize past and ongoing monitoring data as these can inform climate adaptation monitoring needs, and vice versa. For example, our landscape-scale climate vulnerability assessment can be coupled with site-specific data, including monitoring data, to help characterize impacts on a finer scale and aid in prioritizing areas or resources for action. We should work with land managers and ranching partners to identify common indicators, approaches, and focal areas for monitoring. Finding overlap can encourage collaboration and reduce resource burdens among multiple partners.

Opportunities for Building Support and Implementing Adaptation Action

We make recommendations for building support for adaptation implementation, Objective 5, by focusing on communication and collaboration opportunities with agency, ranching, and research partners as well as the broader public. We then highlight current initiatives from USFS and BLM as opportunities for implementing climate adaptation action on the North Rim Ranches.

Building Support through Communication and Collaboration

Collaboration with Ranching Partners

For generations, ranchers have honed an ability to adapt to economic and environmental variability. But, climate change brings unprecedented conditions and a new suite of challenges. Impacts such as reduced water and forage resources projected with intensifying drought will impact livestock and ranching livelihoods (Briske et al. 2015) and increase the challenges of balancing conservation objectives with livestock production (Beschta et al. 2013, 2014; Svejcar et al. 2014). Continuing to work closely with ranching partners will be critical; their unique knowledge can provide localized information that contributes to adaptation planning. Drought management planning should be an important focus of communication and collaboration with ranching partners (Coppock 2011; Briske et al. 2015) as it can facilitate knowledge-sharing and co-development of innovative approaches to climate adaptation (e.g., Brugger et al. 2013). Rotational grazing strategies tailored to reduce stress on vegetation and diversified income strategies to reduce economic stresses will become increasingly important (Coles & Scott 2009; Coppock 2011; Torell et al. 2014).

Seeking out opportunities to collaborate with other conservation-oriented permittees or ranching organizations can also build climate adaptation knowledge. For example, the Quivira Coalition (Quivira Coalition; www.quiviracoalition.org) facilitates workshops and a conversation hub for conservation-oriented ranchers while its Carbon Ranch project explores agricultural strategies that reduce greenhouse gas emissions, improve carbon storage, and improve landscape-scale ecological and economic resilience. The Western Landowners Alliance (Western Landowners Alliance; www.westernlandownersalliance.org) also supports restoration and conservation education and resources for ranchers, including federal policy guidelines. The Nature Conservancy's Dugout Ranch in southern Utah covers over 1000-km^2 (250,000 acres) and hosts the Canyonlands Research Center (Canyonlands Research Center; www.canyonlandsresearchcenter.org), which follows a research allotment model similar to the North Rim Ranches and seeks to understand appropriate management approaches in the face of climate change. These opportunities can aid in building our climate adaptation "toolbox" on the North Rim Ranches and support a greater climate knowledge network across grazed lands.

Collaboration within the Research and Stewardship Partnership

On federal public lands, a strong collaborative relationship between scientists and resource managers contributes to successful climate adaptation (Peterson et al. 2011). For the North Rim

Ranches, the RSP is the science-management partnership that is the hub of the communication and collaboration needed to implement effective adaptation action. Many of the research foci identified in the Applied Research Plan dovetail with research needs identified in this adaptation plan (Grand Canyon Trust et al. 2011). Existing projects demonstrate the partnership's ability to address challenging topics and meet multiple stakeholder needs. Given the complexity of climate change impacts, actions to reduce climate impact vulnerability should follow an adaptive management framework where incremental decision-making and strategic actions build knowledge and long-term monitoring tracks success. In the face of an uncertain future, the RSP should seek out climate adaptation approaches that are flexible, include frequent reassessments of conditions, and be capable of changing direction as climate conditions change (Millar et al. 2007).

To build adaptation support in collaboration with RSP partners, we aim to build our common understanding of climate impact concerns, develop implementation plans for priority adaptation actions, and link decisions to thresholds identified monitoring of climate impacts and climate adaptation action effectiveness. Sharing knowledge and building awareness about climate change concerns is critical to building support for effective integration of climate adaptation into current management planning and actions (Peterson et al. 2011). We intend to engage in knowledge-sharing sessions with land managers within the RSP to foster common understanding of climate change impact projections and primary concerns. Here, the primary focus is on projected impacts, such as increasing drought and wildfire risk, which will then allow for specific planning and applied work. These knowledge-sharing efforts will lay the groundwork for identifying and prioritizing adaptation actions that can be achieved through collaboration. Throughout the process, we will also work closely with agency partners to structure existing monitoring efforts such that they can be easily tailored to meet climate adaptation goals.

Beyond the North Rim Ranches

Understanding climate change impacts and adaptation opportunities beyond the North Rim Ranches is important for building general support for adaptation. We should seek out opportunities and partnerships that build a climate adaptation portfolio on the North Rim Ranches to support the advancement of a greater climate knowledge network (e.g., Comer et al. 2012) across the Colorado Plateau. We also intend to share highlights from this climate change adaptation plan with other land managers, public lands permittees, and stakeholders and communities across the Colorado Plateau with the aim to expand the climate adaptation conversation beyond the North Rim lands. Examples of opportunities for knowledge-sharing include community forums such as the Climate Adaptation Knowledge Exchange (EcoAdapt; www.cakex.org) which provides a repository of case studies, publications, and tools; and DataBasin (Conservation Biology Institute; databasin.org), a free and open-access portal through which to access and share biological, physical, and socio-economic datasets. Other examples include Southwest-focused climate adaption practitioners such as the Southwest Climate Change Network (University of Arizona; www.southwestclimatechange.org) and the Southwest Climate Change Initiative (New Mexico Conservation Science; nmconservation.org/projects/swcci) which provide data resources, news, and workshops for climate adaptation planning. Agency-led initiatives, including the U.S. Department of Agriculture's Climate Hubs and the U.S. Department of Interior's Climate Science Centers, which support science-management collaboration, and Landscape Conservation Cooperatives, which build conservation and restoration knowledge through multi-stakeholder partnership, also provide additional avenues through which to share knowledge.

Building Support through Agency Partner Initiatives

USFS and Kaibab National Forest Initiatives

The USFS acknowledges the importance of mitigating and adapting to climate change and these are primary considerations in agency strategic planning (U.S. Forest Service 2015b). The U.S. Department of Agriculture, which houses the USFS, has developed a national climate change adaptation plan (U.S. Department of Agriculture 2014) and the USFS has developed guidebook for climate adaptation planning at a forest level (Peterson et al. 2011). In select regions, the USFS is working through science-management partnerships to conduct climate change vulnerability assessments and to develop and implement adaptation strategies that are part of long-term planning and management (e.g., Adaptation Partners; www.adaptationpartners.org).

One primary USFS tool is the National Roadmap for Responding to Climate Change (hereafter, Roadmap). This effort links into the U.S. Department of Agriculture's Strategic Plan which calls for "ensur[ing] our national forests and private working lands are conserved, restored, and made more resilient to climate change, while enhancing our water resources." The Strategic Plan states that the U.S. Department of Agriculture should lead efforts to mitigate and adapt to climate change and requires that all national forests construct a climate adaptation and mitigation strategy by 2015. Within this process, the USFS has included the fostering of science, management, and other partnerships to improve the ability to respond to climate change collaboratively. This language highlights an opportunity for the RSP to plug in directly to USFS mandates. The Roadmap also requires a vulnerability assessment of key resources "such as human communities and ecosystem elements" to climate change impacts. The integration of scientific, social, and economic information about climate change exposure and vulnerability of key resources is also required. These directives present another opportunity for our climate change adaptation planning to link with USFS efforts on a landscape scale.

Specific to the North Rim lands, the 2014 Land and Resource Management Plan for the Kaibab National Forest addresses climate change through describing desired conditions for functioning ecosystems as well as recommended management and monitoring approaches (U.S. Forest Service 2014a). Some of the USFS climate-related concerns outlined by USFS overlap with the climate impact scenarios listed in this climate change adaptation plan while others address concerns about increasing climate-related socioeconomic demand (U.S. Forest Service 2014a). The 2014 Land and Resource Management Plan identifies six key management strategies for addressing climate change concerns:

1. Reduce vulnerability by restoring and maintaining resilient native ecosystems;
2. Anticipate increases in forest recreation;
3. Use markets and demand for wood and biomass for restoration, renewable energy, and carbon sequestration;
4. Enhance adaptation by anticipating and planning for intense disturbances;
5. Conserve water; and
6. Monitor climate change influences.

The plan emphasizes an adaptive management approach that is flexible, has incremental steps, and can allow for new information and learning. It also emphasizes integration of science and management though increasing understanding of climate change science as well as local resource conditions and issues, ranking natural resources in terms of climate change vulnerability, developing and implementing options for adapting resources to climate change, and monitoring the effectiveness of on-the-ground management. Some of these strategies are similar to those outlined in this climate change adaptation plan and present an ideal opportunity for collaboration with the Kaibab National Forest.

BLM, Vermilion Cliffs National Monument, and Arizona Strip District Initiatives

The U.S. Department of Interior, which houses the BLM, recognizes climate change as an important influence on public lands and has a coordinated response framework that includes the Climate Change Response Council, the Climate Science Centers, and the Landscape Conservation Cooperatives (U.S. Department of Interior 2016). Within this framework, the BLM has laid out a national landscape-scale approach for managing public lands that broadly addresses many challenges including climate change (U.S. Bureau of Land Management 2010; Leggett 2015). This approach consists of five key components:

1. Rapid Ecoregional Assessments (REAs) that synthesize the best available information about resource conditions and trends;
2. Ecoregional direction which will integrate input from BLM staff, partner agencies, Tribes, and other stakeholders with results from REAs to identify key management priorities;
3. Field implementation that puts into practice management priorities and strategies through revision of BLM land-use plans and Best Management Practices, implementing mitigation measures for authorized land uses, implementing proposed projects and treatments, performing monitoring, and developing shared resource budgets;
4. Monitoring and adaptive management following a formal Assessment, Inventory, and Monitoring Strategy; and
5. Science integration into land management decision-making, including science information from regional Climate Science Centers.

This approach emphasizes the importance of partnerships with regional stakeholders and highlights opportunities within the regional Landscape Conservation Cooperatives. An example of the BLM's landscape approach specifically applied to climate adaptation can be found in its collaboration with NatureServe in southern Nevada (Crist 2012). This pilot project applied the Yale Framework for climate adaptation (Yale Framework; yale.databasin.org) which provides management advice on models and data, an inventory of commonly used datasets utilized by land managers and planners, and a suite of structured options that aid in determining best possible approaches to conservation. Its adaptation objectives follow the framework of Schmitz et al. (2015) and suggest approaches that will protect current patterns of biodiversity, protect large and intact natural landscapes, protect the geophysical setting, maintain and restore ecological connectivity, and identify and manage for species dispersal and climate refugia (Mawdsley et al. 2009; Schmitz et al. 2015).

The BLM's 2010 Colorado Plateau REA covered the full extent of the Colorado Plateau including the North Rim lands (U.S. Bureau of Land Management 2012) and assessed potential future climate conditions and projected climate change impacts. The results from this REA provide an important consideration for climate vulnerability at the Colorado Plateau scale that supplements our North

Rim Ranches-focused vulnerability assessment. The current Vermilion Cliffs and Arizona Strip District Resource Management Plans for the BLM-managed public lands of North Rim lands do not explicitly address climate change. However, the Science Plan for Vermilion Cliffs National Monument cites support for investigations of how “landscape-level compounding stressors such as climate change affect monument objects” and specifically cites the RSP’s Applied Research Plan (Grand Canyon Trust et al. 2011; U.S. Bureau of Land Management 2014). Future management plans must consider climate change impacts in order to develop effective adaptation actions to protect the landscape and its diverse species and ecosystems. Our North Rim Ranches climate change adaptation plan provides a strong foundation for engagement in future management considerations of climate change impacts in this region.

Summary of Recommendations

Prioritize strong relationships with ranching partners built on communication and collaboration. We should work with ranching partners to increase the opportunities to build our shared knowledge of landscape health. We should also work together to develop innovative solutions to the climate change impacts facing the North Rim lands, particularly with respect to drought management planning, as creative solutions will be needed to address livestock management challenges. This collaboration will also enable opportunities for mutual learning and will serve to strengthen our relationships overall.

Support strong and functional collaboration within the Research and Stewardship Partnership. Multi-stakeholder partnerships that emphasize mutual support and information sharing are central components to developing and implementing successful climate adaptation strategies (Peterson et al. 2011; Joyce et al. 2013). Multi-stakeholder collaboration supports co-learning, distributes resource burdens, builds interdependence, and increases the acceptance of management and other decisions (Lemieux et al. 2014). We should continue to prioritize the fostering of functional collaboration within the RSP as it will be critical for developing a broad knowledge base, strengthening shared resources, and building support for taking climate adaptation action.

Identify climate impact knowledge gaps and related adaptation research needs that align with Research and Stewardship Partnership’s goals. The RSP and its Applied Research Plan are a strong foundation for informing and implementing adaptation action. We should identify climate impact knowledge gaps and adaptation research needs that align with or can be addressed by research outlined in the RSP’s Applied Research Plan (Grand Canyon Trust et al. 2011). Where climate adaptation knowledge gaps are not yet addressed, the RSP may decide to append additional research goals.

Collaborate with other conservation-oriented organizations, ranchers, and livestock permittees to share climate impact and adaptation knowledge. The uncertainty and variability of climate change necessitates a flexible and diversified toolbox for addressing impacts. We should seek out opportunities and networks, on and beyond the North Rim lands, which add knowledge, techniques, and decision-making tools to our portfolio of adaptation actions. We should also endeavor to share our own experiences and adaptation approaches through these pathways.

Identify and prioritize opportunities where recommended adaptation actions dovetail with existing climate adaptation efforts by agency partners. We should continue to collaborate with agency partners to achieve common conservation objectives and identify opportunities where the goals of climate-related agency mandates and initiatives align with advancing climate adaptation on the North Rim lands. Through the RSP and the Trust's unique status as both a conservation-advocacy group and a permittee, the Trust can contribute knowledge and facilitate public engagement in key initiatives.

Conclusions

The adaptation actions we take today can reduce the negative effects of climate change impacts tomorrow. Our climate change adaptation plan outlines major climate impact concerns for the North Rim lands and provides a suite of recommendations for adaptation actions and monitoring targeting these impact concerns. This plan builds a foundation for a collaborative implementation strategy that incorporates agency, ranching, and research partners, climate adaptation practitioners, as well as other stakeholders. Planning and taking action now will reduce the long-term costs of climate change impacts and yield mutual benefits. Many of our recommendations align with existing conservation objectives, and represent win-win, "no regrets" actions. Ongoing climate change is a daunting and complex challenge for land managers as they work to reduce the negative impacts of increasing aridity on public lands and to improve resilience to climate change. This climate change adaptation plan for the North Rim Ranches represents a first step in understanding these issues so that we may address this challenge in a proactive and strategic manner.

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APPENDIX A: CLIMATE VULNERABILITY ASSESSMENT

We mapped the relative stress from and vulnerability to climate change on the North Rim Ranches at a landscape scale to provide a tool for understanding on-the-ground climate change impacts. We used datasets representing the amount of climate change projected to impact the landscape, the extent of the influence of these climate changes on the ground, and the capacity for landscape characteristics to facilitate adaptation to these impacts. Such a coarse-scale assessment of climate vulnerability targets the conservation of the ecological conditions that support biodiversity, i.e., conserving “nature’s stage” (Lawler et al. 2015), rather than specific species or ecosystems. While this climate vulnerability assessment is not intended to be the only guidance in identifying and prioritizing adaptation actions, it does provide landscape-level information that can be incorporated into finer-scale species- or ecosystem-level vulnerability assessments.

Climate Vulnerability Assessment Framework

We modeled the climate vulnerability of the North Rim Ranches using a widely-accepted framework for assessing vulnerability to climate change based on a function of three components: exposure to climate change, sensitivity to climate change, and adaptive capacity for climate change (Smit & Wandel 2006; Glick et al. 2011). In this context, the combination of exposure and sensitivity represents the stress from climate change, while adaptive capacity represents the ability to cope with this climate stress. We define each of these terms below.

TERM	DEFINITION
Exposure	Exposure is a measure of the magnitude, rate, and character of climate change that a species or ecosystem experiences (Glick et al. 2011).
Sensitivity	Sensitivity is the degree to which a species or ecosystem is affected, whether adversely or beneficially, directly or indirectly, by climate variability or climate change (Glick et al. 2011; Finch 2012; IPCC 2014).
Adaptive Capacity	Adaptive capacity is the ability of a species or an ecosystem to cope with the impacts of climate change without losing life or some critical function (Glick et al. 2011; Finch 2012).

This three-component climate vulnerability assessment framework has been applied at a range of scales, from species to landscapes. Within this framework, scale-specific representations of exposure, sensitivity, and adaptive capacity are typically modeled individually and then combined to characterize a relative vulnerability to climate change. We reviewed several case studies in which this three-component vulnerability assessment framework has been applied at a landscape scale (Magness et al. 2011; Klausmeyer et al. 2011; Comer et al. 2012; Theobald et al. 2016).

Despite the broad application of the three-component framework, the approaches to modeling each of the three components vary from study to study (Glick et al. 2011; Thompson et al. 2015; Butt et al. 2016; Wade et al. 2016). At both species and landscape scales, there is general agreement that exposure to climate change is represented as a function of change in bioclimatic variables (see *Exposure*). However, for the interrelated sensitivity and adaptive capacity components, the modeling approaches vary. At a species level, characteristics such as habitat area and distribution, phenological mismatch potential, and life history traits have been used to infer sensitivity and/or adaptive capacity (Williams et al. 2008; Bagne et al. 2011; Beever et al. 2015) where climate vulnerability is then be expressed as shifts in species distribution or trait-based indices (Thomas et al. 2004; Pacifici et al. 2015). For a landscape, however, each species, ecosystem, and process will respond to climate in unique ways, with some showing sensitivity or adaptive capacity for certain climate impacts but not for others (Walther 2010; Smith et al. 2014). Despite the challenge of modeling sensitivity and adaptive capacity at a landscape scale, characterizing landscape vulnerability based on climate change exposure alone may not effectively identify areas in need of adaptation (Watson et al. 2013) since other disturbances may be influential (e.g., invasive species, habitat fragmentation).

Landscape-scale vulnerability is influenced by responses from the composite of species, ecosystems, and ecological processes (e.g., hydrologic cycles) within a landscape and how these responses interact over space and time (Glick et al. 2011). To accommodate the complexities associated with landscape-scale modeling of sensitivity and adaptive capacity, case studies have used static, coarse-scale proxies that represent “nature’s stage” (Lawler et al. 2015) rather than species-specific characteristics. Some case studies have employed a combined “potential impact” component (exposure and sensitivity) to represent climate stress (Klausmeyer et al. 2011; Theobald et al. 2016) or a combined “resilience” (sensitivity and adaptive capacity) component to represent the ability to cope with the climate stress (Pocewicz et al. 2014). Other studies have modeled vulnerability components individually, representing sensitivity and adaptive capacity using proxies for landscape-scale disturbance (e.g., invasive species, habitat fragmentation; Magness et al. 2011; Klausmeyer et al. 2011; Comer et al. 2012; Theobald et al. 2016; Virah-Sawmy et al. 2016) and/or landscape-scale characteristics that accommodate shifting community composition and distribution (e.g., biodiversity, geophysical diversity, connectivity; Comer et al. 2012; Theobald et al. 2016). Using these examples, we modeled each vulnerability component individually using static, landscape-scale proxies. We first modeled climate stress for the North Rim Ranches using a combination of exposure and sensitivity and then integrated the adaptive capacity component to determine landscape-scale climate vulnerability.

Landscape-scale Climate Vulnerability

For climate vulnerability of the North Rim Ranches, we mapped a spatial representation of vulnerability using the exposure-sensitivity-adaptive capacity assessment framework at a landscape scale. We first model relative climate stress as a function of exposure and sensitivity

(Klausmeyer et al. 2011; Theobald et al. 2016) using projected climate change (exposure) and geophysical buffering of climate exposure (sensitivity). We then incorporate adaptive capacity based on a proxy for landscape-scale disturbance to determine relative climate vulnerability across the North Rim lands. We modeled each component individually within GIS and explain the derivation of each of these components below. While we do not quantify uncertainty for the model as a whole, we discuss data limitations within each of the component subsections.

Within GIS, we conducted the analyses using continuous grid surfaces (i.e., rasters or pixel-based images) for the full extent of the North Rim lands plus a 1-km (3,281-ft) buffer to reduce potential errors associated with edge effects. We performed all calculations at a 1-km (3,281-ft) resolution (i.e., pixel size). As this was the coarsest resolution of our component data, finer scale (i.e., higher resolution) interpretations of the data, such as in tens of meters, would be less accurate (Hamann et al. 2013).

To combine the each of the components of climate vulnerability, we first standardized and re-scaled each component, and then re-classified each to the same 1 to 10 relative scale. Following Schielzeth (2010), we centered and standardized each continuous component prior to re-classification based on its respective mean and standard deviation values. This refinement improved the component combination by reducing the effect of differences in ranges and units among the components. Then, we re-classified each component to a 1 to 10 relative scale (*sensu* Klausmeyer et al. 2011) using ten quantiles. This relative classification reduced the effect of the different units (e.g., degrees Celsius, millimeters) and absolute scales among components on the overall model outcome, making component combination possible. On the relative scale, we considered 1 to be "worse," contributing to more vulnerability, and 10 to be "better," contributing to less vulnerability. In this way, high exposure to climate change would be at a level 1, "worse," as it contributes to more relative vulnerability, whereas low sensitivity and high adaptive capacity would each be at a level 10, "better," since these conditions would reduce relative vulnerability. Once each component was re-classified, we combined the three elements together via multiplication and re-scaled to 1-10 again to obtain a composite assessment of stress (exposure × sensitivity) and vulnerability (stress × adaptive capacity). Our map of relative climate stress is in **Figure 16** and our map of relative climate vulnerability is in **Figure 17**. We detail the component modeling in the following subsections.

Exposure

Within this assessment framework it is typical to represent exposure to climate change as a bioclimatic variable that is relevant to a particular species or landscape, and several candidates exist (e.g., change in temperature, amount of precipitation as snowfall, number of frost-free days). Klausmeyer et al. (2011) used annual precipitation, January minimum temperatures, and July maximum temperatures to assess exposure for the state of California while the Bureau of Land Management (2012) used average annual, summer, and winter temperature and precipitation for climate vulnerability on the Colorado Plateau. For our landscape-scale assessment, we selected both average temperature and average precipitation and opted for annual rather than seasonal variables. We represented the exposure to climate change as a combination of the changes in mean annual temperature and in mean annual precipitation, where the changes were determined as the differences between projected (2041-2070) and current (1981-2010) values.

Current Climate

For current climate, we modeled the mean annual temperature and mean annual precipitation using 30-year climate "normal" data for the 1981-2010 period from PRISM (PRISM Climate Group; prism.oregonstate.edu) obtained from AdaptWest (AdaptWest Project; adaptwest.databasin.org). We selected this current climate dataset to match the source of our projected data (i.e., AdaptWest); PRISM-based current climate models have been shown to high agreement with weather station (i.e., observed) data (Wang et al. 2006).

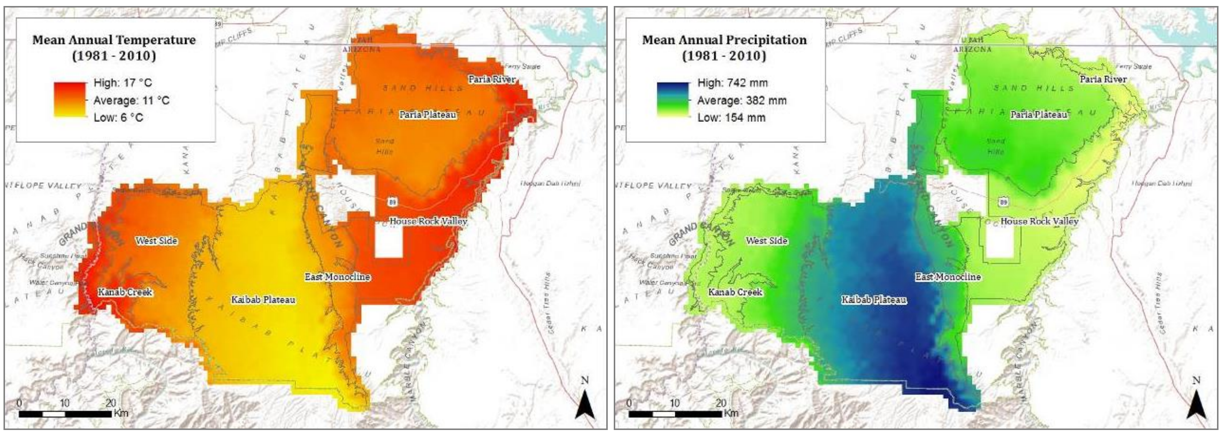

Figure 10 – Current Climate of the North Rim Ranches. We characterized the current climate of the North Rim Ranches can using recent (1981-2010) averages for mean annual temperature (°C, left) and mean annual precipitation (mm, right). For mean annual temperature (left), warmer values are darker (red) and cooler values are lighter (yellow). For mean annual precipitation (right), wetter values are darker (blue) and drier values are lighter (yellow). Values are rounded to the nearest whole number (maps based on data from AdaptWest [AdaptWest Project; adaptwest.databasin.org]).

From 1981-2010, mean annual temperature has ranged from 6 to 17°C (43 to 63°F) while mean annual precipitation has ranged from 154 to 742 mm (6 to 29 in) across the landscape (**Figure 10**). The Kaibab Plateau has been the coldest and wettest geographic area, with average temperature at 8°C (46°F) and average precipitation at nearly 600 mm (24 in) per year. The Kanab Creek, House Rock Valley, and Paria River geographic areas have been the warmest and driest, each with average temperatures above 14°C (57°F) and average precipitation below 300 mm (11 in) per year.

Projected Climate and Climate Change

We modeled projected climate within GIS using mean annual temperature and mean annual precipitation data for mid-century (2041-2070) available from AdaptWest (AdaptWest Project; adaptwest.databasin.org). Data were obtained from an ensemble average based on 15 Coupled Model Intercomparison Project Phase 5 (CMIP5) regionally-downscaled (1-km [3,281-ft]) models. The 15 CMIP5 models represent all major clusters of similar atmosphere-ocean general circulation models. An ensemble average was selected over the use of one single model to present a more robust estimation of exposure to climate (Harris et al. 2014). We used data for the representative concentration pathway (RCP) of 8.5, the highest of four pathways representing greenhouse gas emissions for the 21st century including atmospheric concentrations, air pollutant emissions, and land use. RCP8.5 represents very high greenhouse gas emissions (relative to RCPs 2.6, 4.5, and 6.0) without additional efforts to constrain emissions (IPCC 2014) and is equivalent to +8.5 W/m^2 of radiative forcing in 2100 compared to pre-industrial values (IPCC 2013).

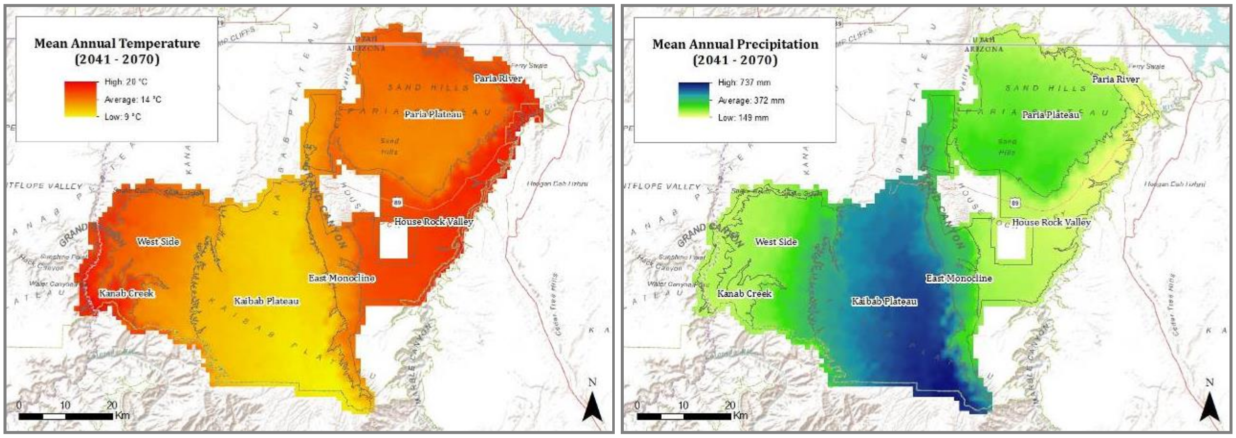

Figure 11 – Projected Climate for the North Rim Ranches. We characterized projected climate for the North Rim Ranches using mid-century projections (2041-2070) for mean annual temperature (°C, left) and mean annual precipitation (mm, right). For mean annual temperature (left), warmer values are darker (red) and cooler values are lighter (yellow). For mean annual precipitation (right), wetter values are darker (blue) and drier values are lighter (yellow). Values were rounded to the nearest whole number (maps based on data from AdaptWest [AdaptWest Project; adaptwest.databasin.org]).

For 2041-2070, mean annual temperatures are projected to range from 9 to 20°C (40 to 68°F) while mean annual precipitation are projected to range from 149 to 737 mm (6 to 29 in) across the landscape (**Figure 11**). Variation in temperature and precipitation across the North Rim Ranches is consistent with current climate: the Kaibab Plateau remains the coldest and wettest while Kanab Creek, House Rock Valley, and the Paria River remain the warmest and driest.

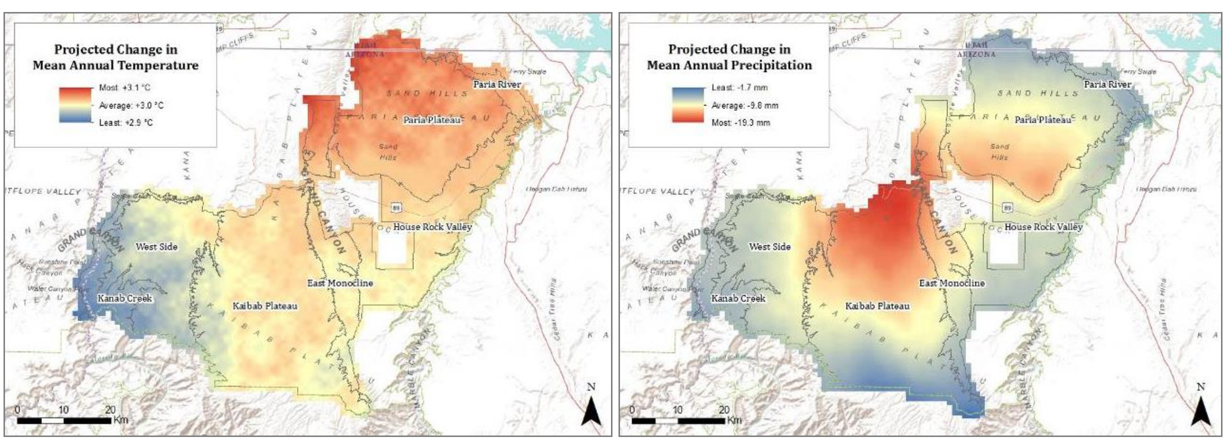

Figure 12 – Projected Climate Change for the North Rim Ranches. We characterized climate change by mid-century (2041-2070) for the North Rim Ranches using mean annual temperature (°C, left) and mean annual precipitation (mm, right). For both mean annual temperature (left) and mean annual precipitation (right), more change is depicted in red while less change is depicted in blue. Values were rounded to the nearest whole number (maps based on data from AdaptWest [AdaptWest Project; adaptwest.databasin.org]).

We calculated the difference between the projected (**Figure 11**) and current (**Figure 10**) climate variables within GIS. For changes in mean annual temperature, we calculated a +2.9 to +3.1°C (+5.2

to +5.6°F) increase across the landscape (**Figure 12**). We calculated the most warming to occur for the Paria Plateau and northern portion of the East Monocline and the least warming to occur for the West Side and Kanab Creek. The warming projected for the North Rim Ranches is consistent with the literature, albeit on the higher end of other projected ranges. Warming projections based on a CMIP3[2] model basis from Garfin et al. (2013) range from +1.1 to +3.3°C (+2 to +6°F) for similar time periods (2041-2070 compared to 1971-2000).

For changes in mean annual precipitation, we calculated a -1.7 to -19.3 mm (0.07 to 0.8 in) decrease across the landscape (**Figure 12**), representing approximately a 0.1 to 5.0 percent change (compared to current mean annual precipitation). We calculated the most change to occur on the northern portion of the Kaibab Plateau, northern portion of the East Monocline, and the southern portion of the Paria Plateau. Our calculations of small but negative average change are consistent with the literature (Garfin et al. 2013); although, the highest calculated change is slightly above the projected 4 percent change for the Southwest overall by 2055 (Garfin et al. 2013).

[2] The CMIP5 model, the basis for analysis in the IPCC's Fifth Assessment Report (IPCC 2014), is generally considered to have warmer projections for RCP8.5 than A2 scenario in the CMIP3 model, the basis for analysis in the IPCC's Fourth Assessment Report (IPCC 2007). Additional differences between the models and model processing can be found in this resource: (U.S. National Oceanic and Atmospheric Association 2015).

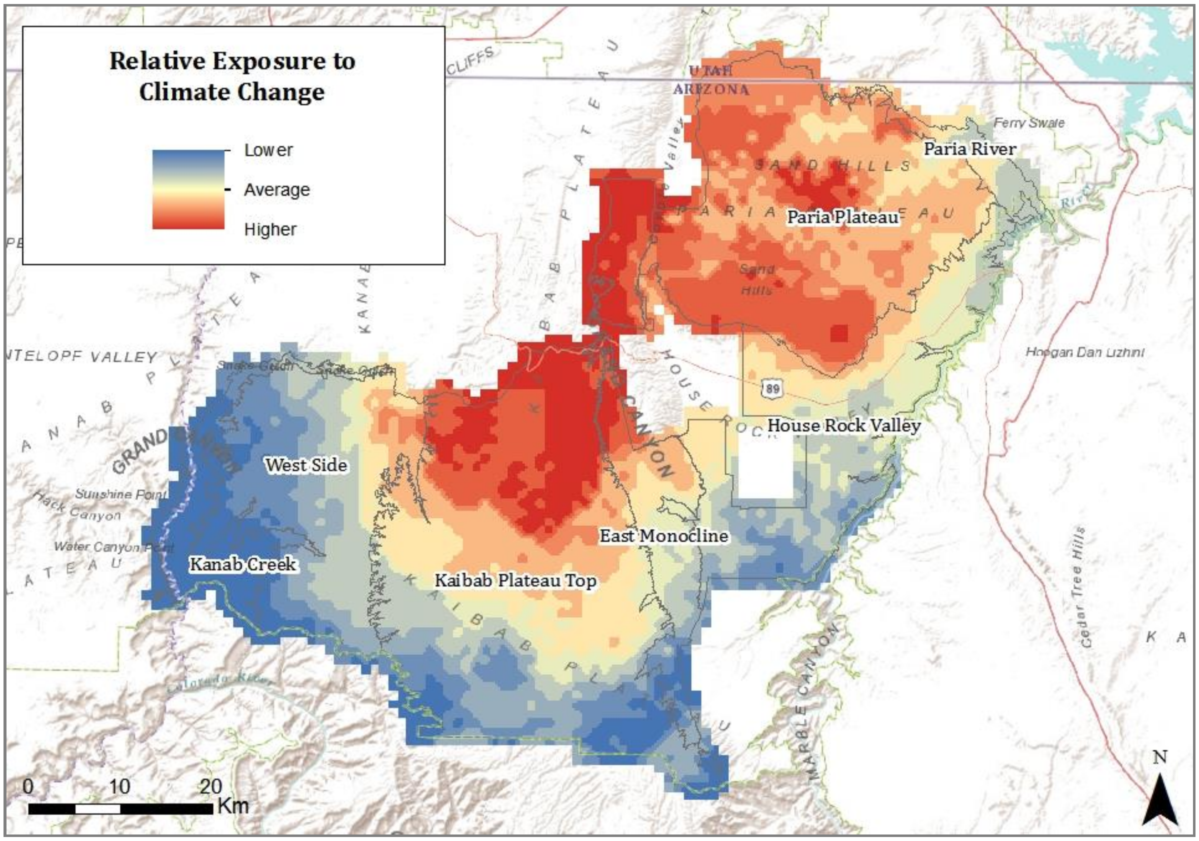

Figure 13 – Relative Exposure to Climate Change on the North Rim Ranches. We mapped relative exposure to climate change for the North Rim Ranches based on landscape-scale estimates of changes in mean annual temperature and mean annual precipitation between the current climate "normal" (1981-2010) and a projected climate "normal" (2041-2070). Areas in red represent areas of higher exposure relative to the rest of the landscape, while areas in blue represent areas of lower exposure.

After centering and standardizing the two exposure components, change in mean annual temperature and change in mean annual precipitation (**Figure 12**), we re-scaled each on the 1 to 10 scale using quantiles. Greater change was considered a 1 and less change was considered a 10. The two components were combined via multiplication and then again re-scaled to 1 to 10. Our final exposure layer (**Figure 13**) depicted the northern portion of the Kaibab Plateau, the northern portion of the East Monocline, and much of the Paria Plateau as areas of relatively higher exposure to climate change. Kanab Creek, House Rock Valley, and the southern Kaibab Plateau are depicted as areas of relatively lower exposure to climate change.

Sensitivity

For sensitivity to climate change, we used a regionally-specific land facet diversity layer developed by and shared by C. Albano (Albano 2015). Land facets are physiographic settings of biological activity and are considered to represent environmental heterogeneity which, in turn, is a surrogate for genetic and species diversity (Dauber et al. 2003; Hjort et al. 2015; Theobald et al. 2015).

Landscapes with higher land facet diversity are considered to be less sensitive to climate change as geophysical features moderate climate factors such as wind exposure and solar radiation and allow for a greater variety of temperature and moisture conditions within a given area (Dobrowski 2011; Albano 2015). In areas with lower geophysical diversity, the rate of climate change and related biological impacts will be greater (Loarie et al. 2009; Ackerly et al. 2010). Areas with greater diversity may act as climate refugia and buffer climate impacts, present a greater variety of habitats, and allow for species survival outside of their main distribution (Dobrowski 2011). Because species shifts are influenced by microclimate variation, areas of high land facet diversity are critical for long-term survival (Anderson et al. 2014), particularly for limited mobility species (Dobrowski 2011; Albano 2015).

Representations of land facet diversity typically include measures of soil and topographic complexity (Beier & Brost 2010; Theobald et al. 2015; Albano 2015). For the land facet diversity layer that we used in our vulnerability assessment, Albano (2015) considered characteristics of soil type, topographic heat load, topographic complexity, and elevation. In addition to the robust modeling approach, this layer was specifically calibrated for the Southwest and developed to guide climate adaptation planning (Albano 2015), making it an ideal representation of sensitivity to climate change on the North Rim Ranches.

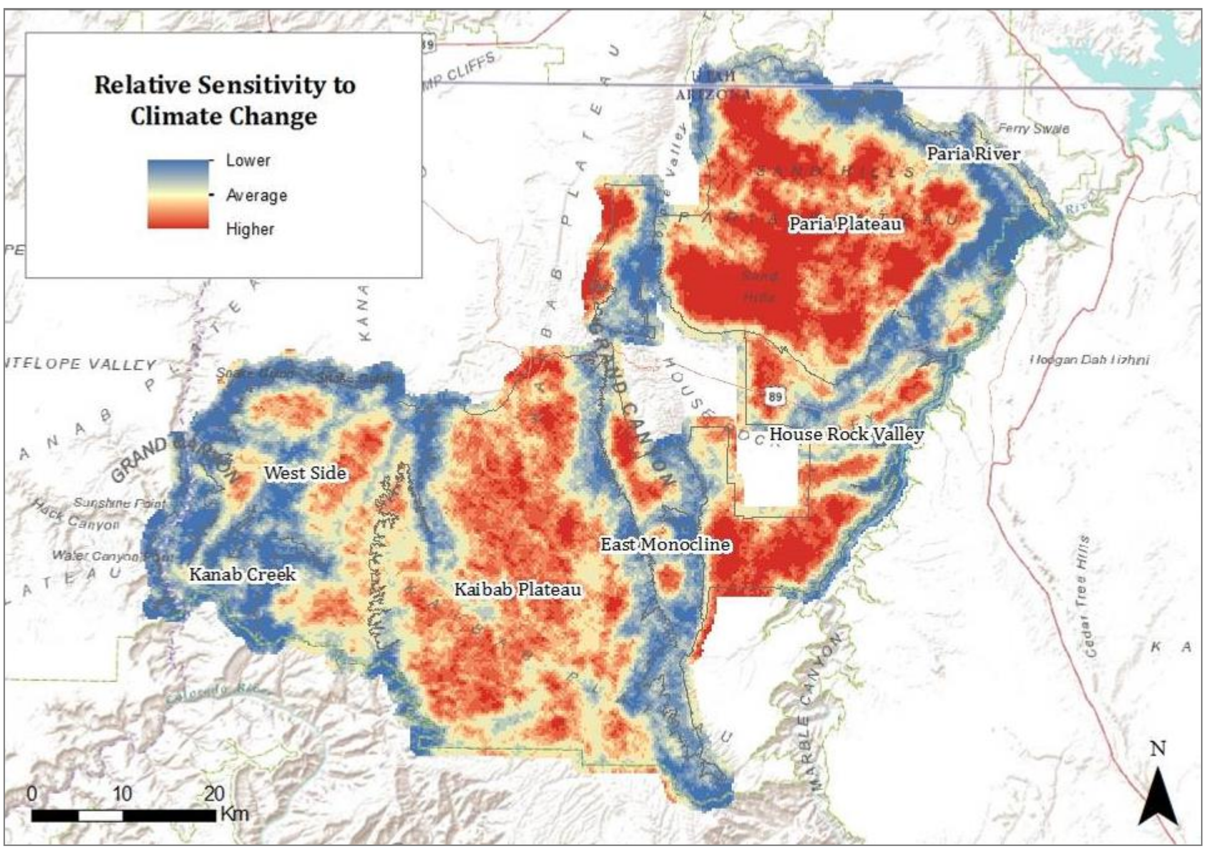

Figure 14 – Relative Sensitivity to Climate Change on the North Rim Ranches. We mapped relative sensitivity to climate change for the North Rim Ranches based on a landscape-scale estimate of land facet diversity (Albano 2015). Areas in red represent areas of higher sensitivity relative to the rest of the landscape, while areas in blue represent areas of lower sensitivity.

We centered and standardized the land facet diversity layer and re-scaled it to 1 to 10 using quantiles. Areas of lower land facet diversity were considered a 1 while areas of greater land facet diversity were considered a 10. In our final sensitivity layer (**Figure 14**), we estimated that sensitivity to climate change was higher across much of the West Side, Kaibab Plateau, House Rock Valley, and Paria Plateau relative to other areas on the North Rim Ranches. These more sensitive areas exhibited lower land facet diversity and may experience climate change impacts at a higher rate than less sensitive, higher land facet diversity areas. While adaptation actions should focus on more climate vulnerable areas, conservation and restoration in areas of lower sensitivity is also critical to maintain or improve potential climate refugia.

Adaptive Capacity

Adaptive capacity at a landscape scale can be characterized by the level of ecological integrity across a landscape; areas that are less compromised will likely have greater capacity to adapt to climate change and vice versa. To model the adaptive capacity component of climate vulnerability, we used a landscape intactness layer based on landscape "naturalness" and connectivity factors developed and shared by D. Theobald (Theobald et al. 2012). Landscape intactness is characterized by high landscape connectivity, i.e., low habitat fragmentation, and high ecological integrity, i.e., where natural evolutionary and ecological processes take place and can support and maintain ecosystems and biodiversity (as reviewed by Theobald 2013). These characteristics are important factors in the ability of species to maintain gene flow, migrate, and adapt to projected climate shifts through dispersal (Heller & Zavaleta 2009; Glick et al. 2011; Finch 2012). Reducing threats to ecological integrity (e.g., invasive species) and improving landscape connectivity are considered to be two of the most common climate adaptation strategies (Heller & Zavaleta 2009).

Other landscape-scale vulnerability assessments have represented adaptive capacity in similar ways using road density, land protection, and habitat fragmentation (Comer et al. 2012; Theobald et al. 2016). Similar landscape intactness and connectivity metrics have also been coupled with land facet diversity metrics to aid in conservation area and climate adaptation planning (Anderson et al. 2014; Dickson et al. 2014).

The layer developed by Theobald (2012) evaluated the connectivity of "natural areas" where human modification of land cover and human activities were considered minimal, thereby facilitating wildlife movement and allowing ecological processes to occur naturally. The layer also considered land cover modification, residential housing, roads and railways, highway traffic, and resource extraction as factors in human modification and included canopy cover and topographic slope as influences on connectivity (Theobald 2010; Theobald et al. 2012). Of course, other factors such as invasive species and ranching infrastructure (i.e., fences) influence connectivity, but these factors have greater influence at ecosystem or species levels and should be considered in finer-scale assessments. Because our representation of adaptive capacity included only relatively static components, rather than more dynamic climatic or biotic components, it provided a landscape-level representation ideal for long-term adaptation planning.

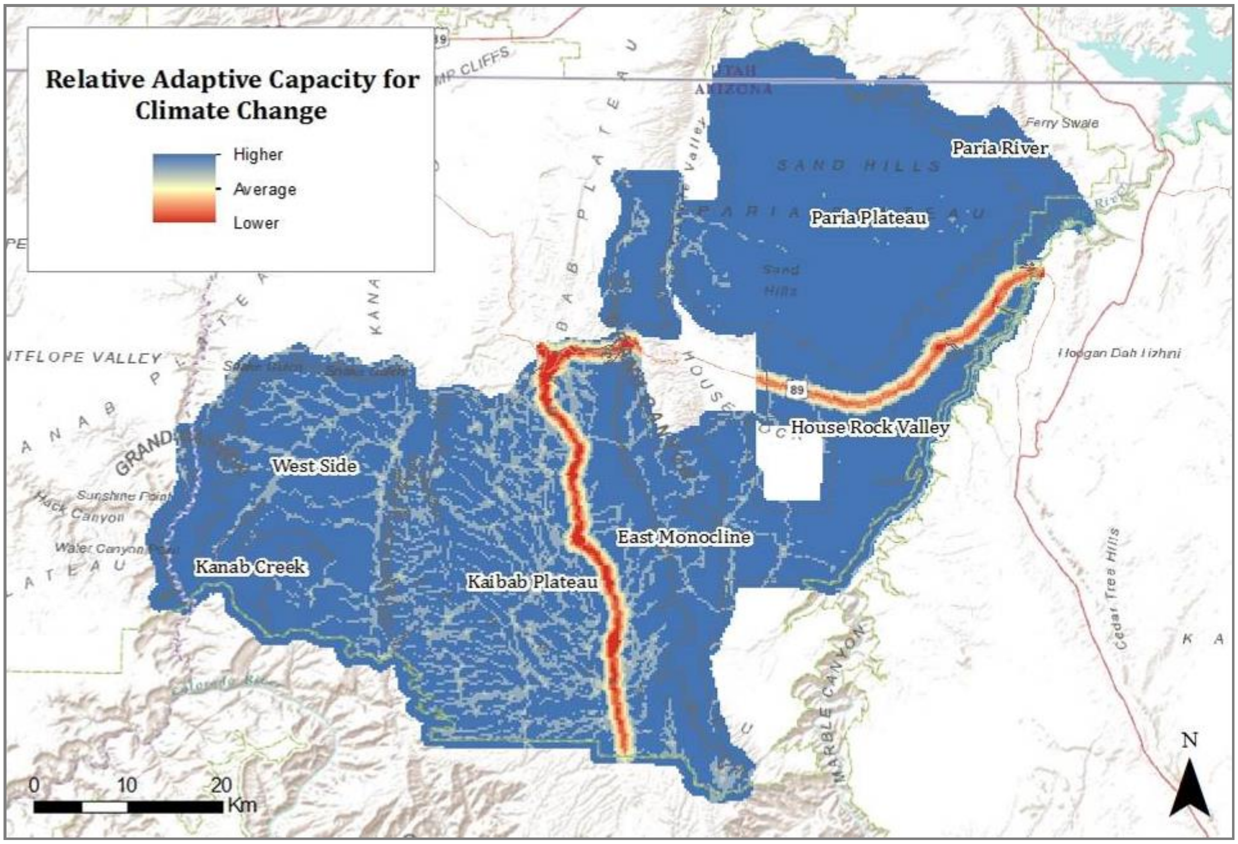

Figure 15 – Relative Adaptive Capacity for Climate Change on the North Rim Ranches. We mapped relative adaptive capacity for climate change on the North Rim Ranches based on a landscape-scale estimate of landscape intactness (Theobald et al. 2012). Areas in red represent areas of lower adaptive capacity relative to the rest of the landscape, while areas in blue represent areas of higher adaptive capacity.

We centered and standardized the landscape intactness layer and re-scaled it to 1 to 10 using quantiles. Areas of lower intactness were considered a 1 while areas of greater intactness were considered a 10. In our final adaptive capacity layer (**Figure 15**), the Highway 89A and Highway 67 corridors stood out as primary factors in landscape intactness while other dirt roads likely contributed to the closer-to-average adaptive capacity values across the Kaibab Plateau and West Side. Despite the presence of dirt roads on the Paria Plateau, the area's comparatively greater remoteness likely contributed to the area's higher adaptive capacity.

Climate Change Stress and Vulnerability

We combined the exposure and sensitivity components to obtain a characterization of the relative climate stress across the landscape. This combination represents the exposure to projected changes in temperature and precipitation as moderated by land facet diversity (**Figure 16**).

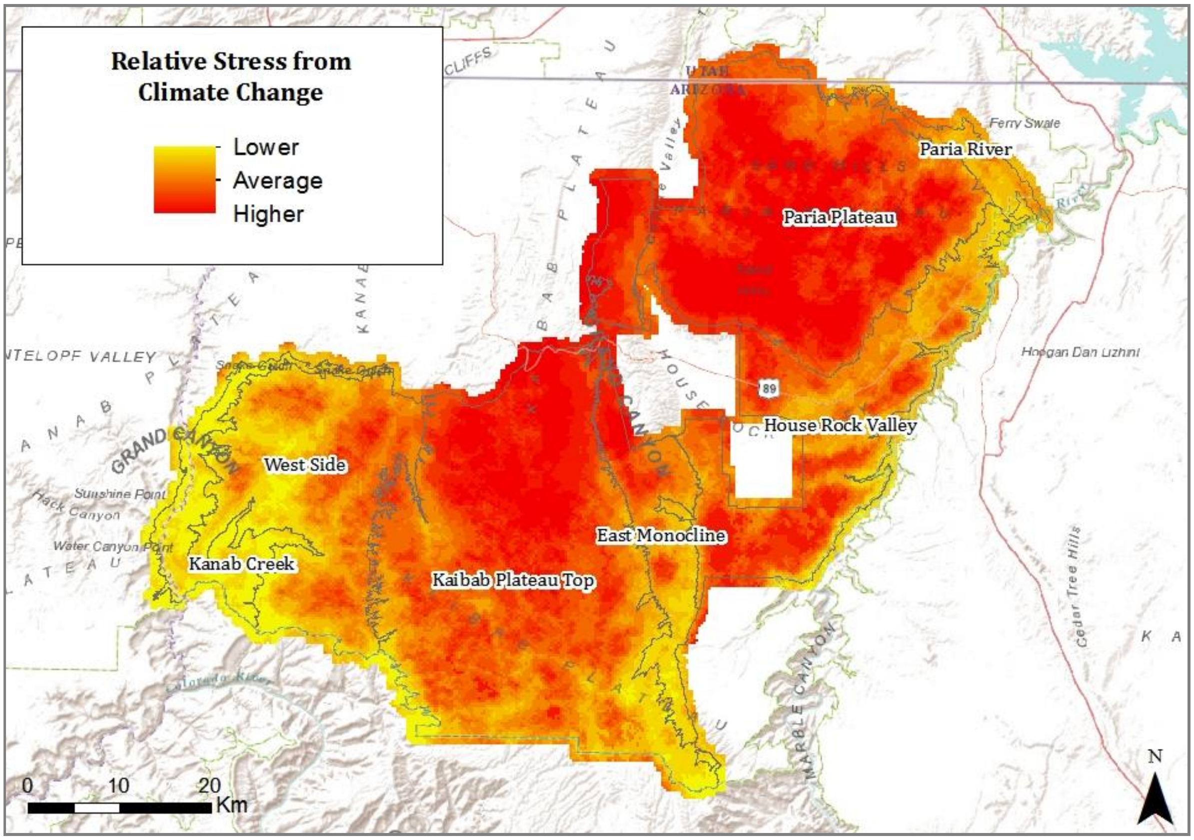

Figure 16 – Relative Stress from Climate Change on the North Rim Ranches. We mapped relative climate stress for the North Rim Ranches based on landscape-scale estimates of exposure and sensitivity. Areas in red (darker) represent areas of higher stress relative to the rest of the landscape, while areas in yellow (lighter) represent areas of lower stress.

Based on our exposure × sensitivity model, we found substantial variation across the North Rim lands for relative climate stress (**Figure 16**). The northern portion of the Kaibab Plateau, the southern portion of the Paria Plateau, and much of House Rock Valley and the East Monocline exhibit a higher stress from climate change relative to the rest of the landscape. Areas where there is higher exposure to climate change (northern Kaibab Plateau, Paria Plateau) and higher sensitivity (Kaibab Plateau, House Rock Valley, Paria Plateau), exhibited the most stress relative to other areas. Kanab Creek and portions of the Paria River and West Side had lower climate stress relative to the rest of the landscape and were also areas of lower exposure and lower sensitivity.

For our final vulnerability map, we combined climate stress (exposure × sensitivity) with adaptive capacity (climate stress × adaptive capacity). This combination represents how climate stress is moderated by adaptive capacity. More vulnerable areas are those with higher climate stress and lower adaptive capacity and less vulnerable areas are those with lower climate stress and higher adaptive capacity.

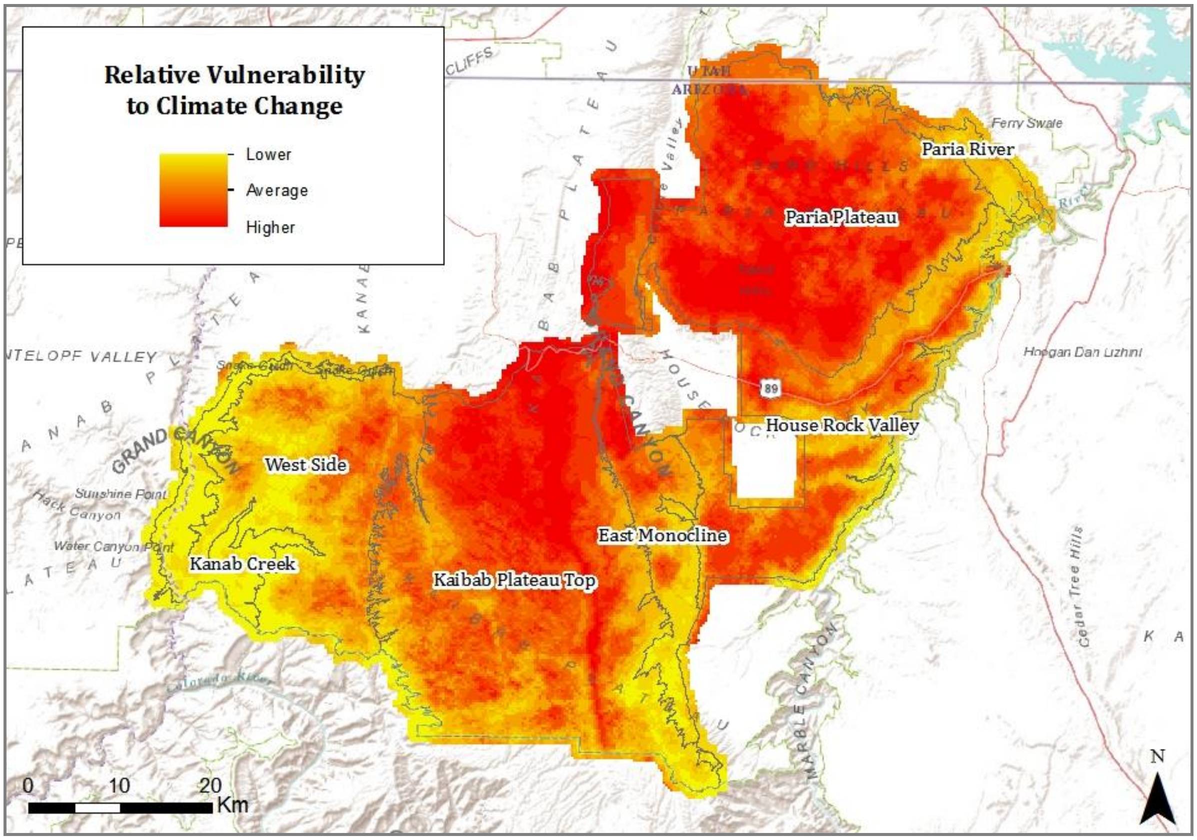

Figure 17 – Relative Vulnerability to Climate Change on the North Rim Ranches. We mapped relative climate vulnerability for the North Rim Ranches landscape based on landscape-scale estimates of climate stress and adaptive capacity. Areas in red (darker) represent areas of higher vulnerability relative to the rest of the landscape, while areas in yellow (lighter) represent areas of lower vulnerability.

We found substantial variation across the North Rim lands for our estimate of relative climate vulnerability (**Figure 17**). The northern portion of the Kaibab Plateau, the southern portion of the Paria Plateau, and much of House Rock Valley and the East Monocline exhibit a higher vulnerability to climate change relative to the rest of the landscape. Areas where there is higher stress from climate change and lower adaptive capacity exhibited the highest vulnerability relative to other areas. Kanab Creek and portions of the Paria River and West Side had lower climate vulnerability relative to the rest of the landscape and were also areas of lower stress and higher adaptive capacity.