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Natural Resource Stewardship and Science

Climate Change Scenario Planning to Guide Research and Resource Management at White Sands National Park

Natural Resource Report NPS/WHSA/NRR—2021/2261

ON THE COVER
Photograph of sunset over the dune field at White Sands National Park.
Credit: NPS

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Natural Resource Report NPS/WHSA/NRR—2021/2261

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Executive Summary

White Sands National Park (WHSA), located in the northern portion of the Chihuahuan Desert, protects 40 percent (115 square miles [mi^2]) of the 275-mi^2 White Sands dune field (Kocurek et al. 2006)—the world's largest gypsum dune field. The dune field is classified as a wet aeolian system that is intricately tied to both surface and groundwater hydrological processes. Wet sediments are found just below dune surfaces, and groundwater typically occurs at a depth of just a few feet below the base of the dunes. This unique system supports a diverse array of plants and wildlife, including many endemic species. Primary ecosystem drivers for the dune field include precipitation, groundwater hydrology, winds, floods, and droughts.

Alterations in temperatures and precipitation, as are expected with ongoing change in climatic conditions, can significantly alter geologic and biological systems in the park. Most climate models project a temperature increase in the southwestern US, whereas projected precipitation changes among models include both decreases and increases. An on-site weather station in the park shows an overall precipitation increase since 1950. The challenge for the park is how best to 1) steward park resources in an era of rapid, directional change in fundamental drivers of ecological condition, and 2) encourage research approaches that support and enhance understanding of key vulnerabilities.

To better inform both short- and long-term resource management and research activities, the park, the region, the National Park Service (NPS) Chihuahuan Desert Inventory and Monitoring Network (CHDN), the New Mexico State Climatologist's Office, several academic institutions, and the NPS Climate Change Response Program worked together to design and conduct the White Sands Scenario Planning Workshop in June 2017. Workshop participants included a range of experts on climate, hydrology, and ecology from several academic institutions, as well as the park, New Mexico State Climatologist's Office, and the Chihuahuan Desert Inventory and Monitoring Network. The WHSA workshop used a refined, qualitative climate change scenario planning approach focused on expert opinion and synthesis of pre-existing science, and solicited expert opinion from the group via a structured process to identify and/or hypothesize impacts to resources under three divergent but plausible climate futures: 1) Warm/No Precipitation Change, 2) Hot and Wet and 3) Hot and Dry This process of identifying resource vulnerabilities under each climate future not only developed a set of robust climate-resource scenarios to help guide management, but also identified key potential vulnerabilities that need to be better understood. Specifically, wherever participants identified a potential adverse impact to a resource under a given scenario (see Table 2) but indicated low certainty about that resource's vulnerability, a potential resource-specific research need has been identified.

Participants also identified the following general research-related actions as important to better understand climate change vulnerabilities and impacts on WHSA resources:

- Integrate research among different disciplines.
- Have more frequent collaborative meetings among researchers.

- Enhance science communication and translation so that there is ever-improving linkage between the information needs of the park's decision makers and the priority science activities to address those needs.
- Enhance baseline inventories for lesser-understood species/ecosystem components and enhance research to meet data/information gaps.
- Enhance existing and find new funding sources to continue priority research.

Improved, scenario-based, understanding of resource vulnerabilities arising from integrated, collaborative, priority research efforts will ultimately empower WHSA to develop adaptation strategies to effectively steward park resources under a range of potential future climate conditions.

Soap tree yucca (*Yucca elata*) in the dunes at White Sands National Park (NPS)

Acknowledgements

The authors would like to thank the NPS Climate Change Response Program for support in planning and implementing the WHSA Scenario Planning Workshop and for providing funding for the final publication of the technical report. Brendan Moynahan (Rocky Mountain Cooperative Ecosystems Studies Unit) proved invaluable as peer review manager, providing oversight and guidance in finalizing this document. We would also like to thank Don Weeks (NPS Intermountain Regional Office) and Brian W. Miller (US Geological Survey [USGS], North Central Climate Adaptation Science Center) for their detailed review of the technical report. Most of all, we would like to thank the many researchers and workshop participants for their technical expertise and enthusiasm that made the workshop highly successful.

Workshop Purpose and Need

This report summarizes discussions and outcomes from a one-day climate change scenario planning workshop for White Sands National Park (WHSA). WHSA is located southwest of Alamogordo, New Mexico, in the Tularosa Basin, and consists of the southern part of the 275-mi^2 White Sands dune field, the largest gypsum dune field in the world.

The entire dune field is held together by sediment moisture, a biocrust, and a high-water table at the base of the dunes (the water table occurs only a few feet below the base of the dunes). The system is in a fragile balance because tons of gypsum are lost every year as dust, and simultaneously replenished from new gypsum crystals resulting from large precipitation (flooding) and drying events often associated with La Niña and El Niño.

Although a great deal of scientific investigation has taken place at the park, scientists are just beginning to understand the complex relationships between sediment moisture in the dunes, groundwater, and regional aquifer that sustain the unique ecology of WHSA.

The overarching goal for the workshop was to synthesize existing scientific knowledge to 1) support climate-informed resource management in the park and 2) help guide climate-related research in the park. To support this goal, the workshop convened a diverse group of researchers in the Tularosa Basin who are closely associated with the park to

1.) share information about ongoing studies and explore opportunities for further research and collaboration,
2.) explore current climate science and plausible climate futures for the region, and
3.) harness participant expertise in a process to develop climate-resource scenarios that can inform resource management and identify critical uncertainties that require research.

To better inform both short- and long-term resource management and research activities, the park, region, National Park Service (NPS) Chihuahuan Desert Inventory and Monitoring Network (CHDN), New Mexico State Climatologist's Office, several academic institutions, and the NPS Climate Change Response Program collaborated to design and conduct the White Sands Scenario Planning Workshop in June 2017 (see Appendix A). Workshop participants included experts on WHSA climate, hydrology, and on the unique ecology (both biological and physical resources) of the park.

Scenario-based understanding and actions developed by the workshop will help WHSA steward its resources through "an era of continuous change that is not fully understood" (NPSAB 2012) by 1) identifying key adaptation strategies that address the range of potential future climate conditions and 2) guiding and coordinating research to strategically improve our understanding of park resource vulnerabilities.

Introduction to Scenario Planning

Managers cannot predict precisely how climate change will affect national parks and protected areas; however, protected area managers can apply the most current information on climate change, work with irreducible uncertainties, develop strategies to guard against future risk, and identify indicators that allow them to recognize changes early. Such actions may allow managers to react to future challenges with speed and confidence. The accelerated rate in the production of scientific information that must be understood and conveyed challenges careful stewardship of natural and cultural resources. Successful action in the face of climate change requires not only greater understanding of scientific data, but also using this understanding to adaptively manage park operations, facility management, and communications.

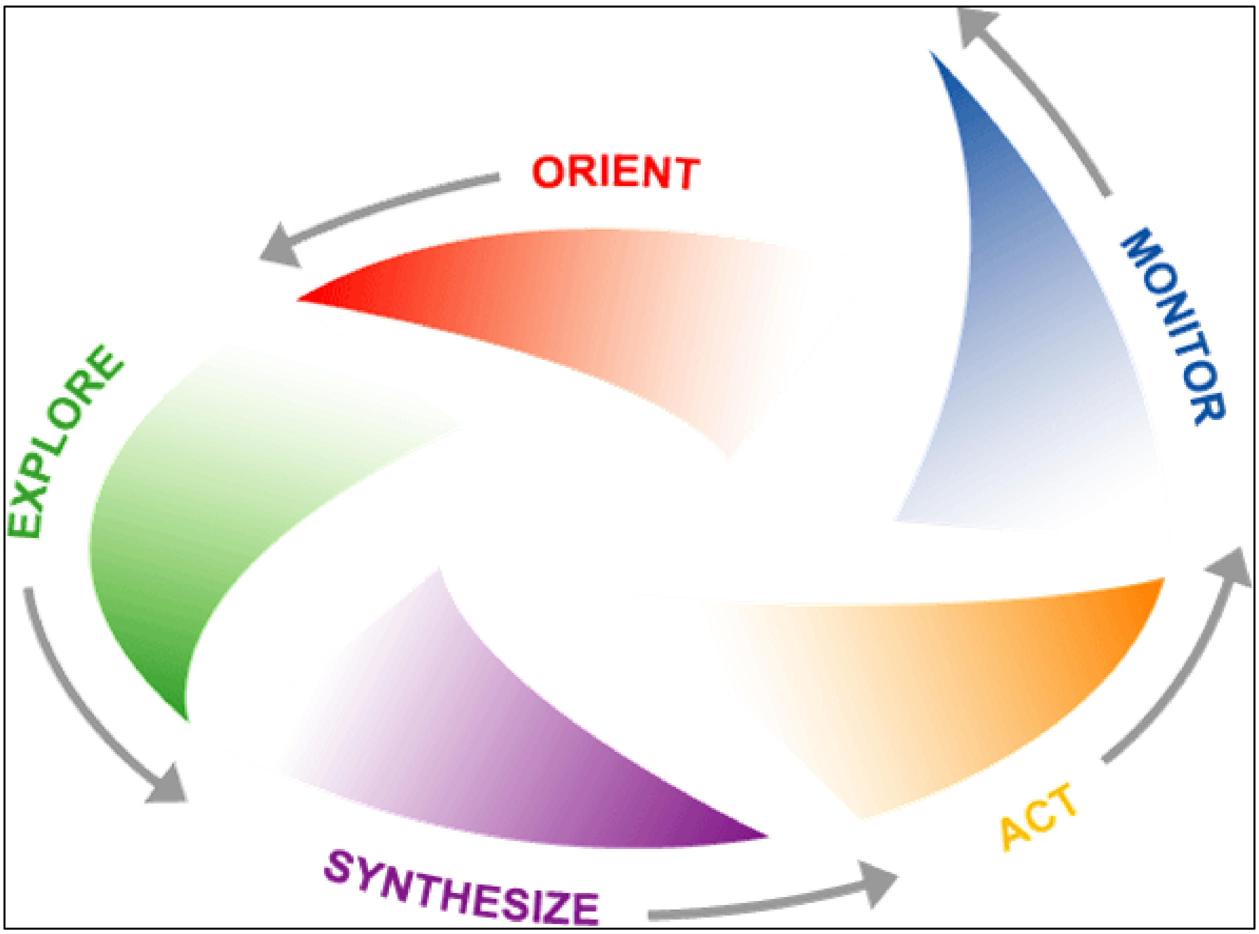

Figure 1. Five-step scenario planning process (©GLOBAL BUSINESS NETWORK 2010) (NPS 2013).

The National Park Service uses scenarios as an effective method to achieve these objectives (NPS 2013; Star et al. 2016; Runyon et al. 2020). A scenario is essentially a plausible, internally consistent story about the future that challenges us to consider how we would operate under novel conditions. Scenario work explores and describes characteristics of several plausible futures, enabling managers to consider how to define and meet goals (desired conditions) under new and changing circumstances. The scenario-building process involves one or more workshops organized by a core group of individuals and attended by key stakeholders. In advance of the WHSA Scenario Planning Workshop, core team members interviewed workshop participants and stakeholders to understand the assumptions, perspectives, and important management challenges associated with climate change. The participants and core team then identified specific questions or issues to explore using scenarios.

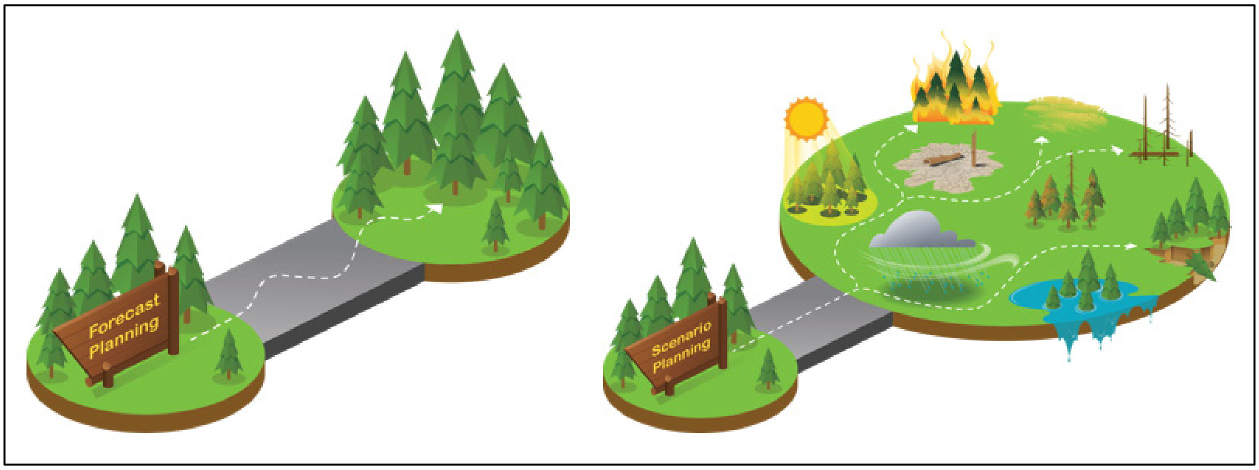

Figure 2. Forecast-based approaches to planning (left) use predictions of a single future. Scenario planning (right) works with a set of plausible future conditions and provides a framework to support decisions under conditions that are uncertain and uncontrollable (NPS).

By building scenarios based on projected future climate trends and effects and their associated degree of certainty, managers can assess relative risk, test important decisions, develop strategies or contingency actions, and identify key indicators that can assist in signaling key changes in an ecosystem.

The WHSA Scenario Planning Workshop provided researchers and park partners the opportunity to identify and/or hypothesize impacts to resources in an open and integrated fashion. By using the climate futures identified for WHSA, the scenario planning process helps focus research to support forward-looking, climate-informed resource management.

Biophysical Systems and Climate Drivers for White Sands National Park

WHSA is part of the Chihuahuan Desert Ecoregion in south-central New Mexico and includes 144,000 acres of bajadas (a series of fan-shaped deposits from the deposition of sediment along a mountain front), alkali flats, playas (areas of flat land that can temporarily hold water, but that dry up quickly with evapotranspiration), and 40% of the world's largest gypsum dune field (Nadeau et al. 2017). The elevation in the park ranges from 3,891 feet [ft] at Lake Lucero to 4,114 ft in the foothills of the San Andreas Mountains on the west side of the park. Average annual precipitation is approximately 8 inches [in] (CHDN 2017) (Figure 3).

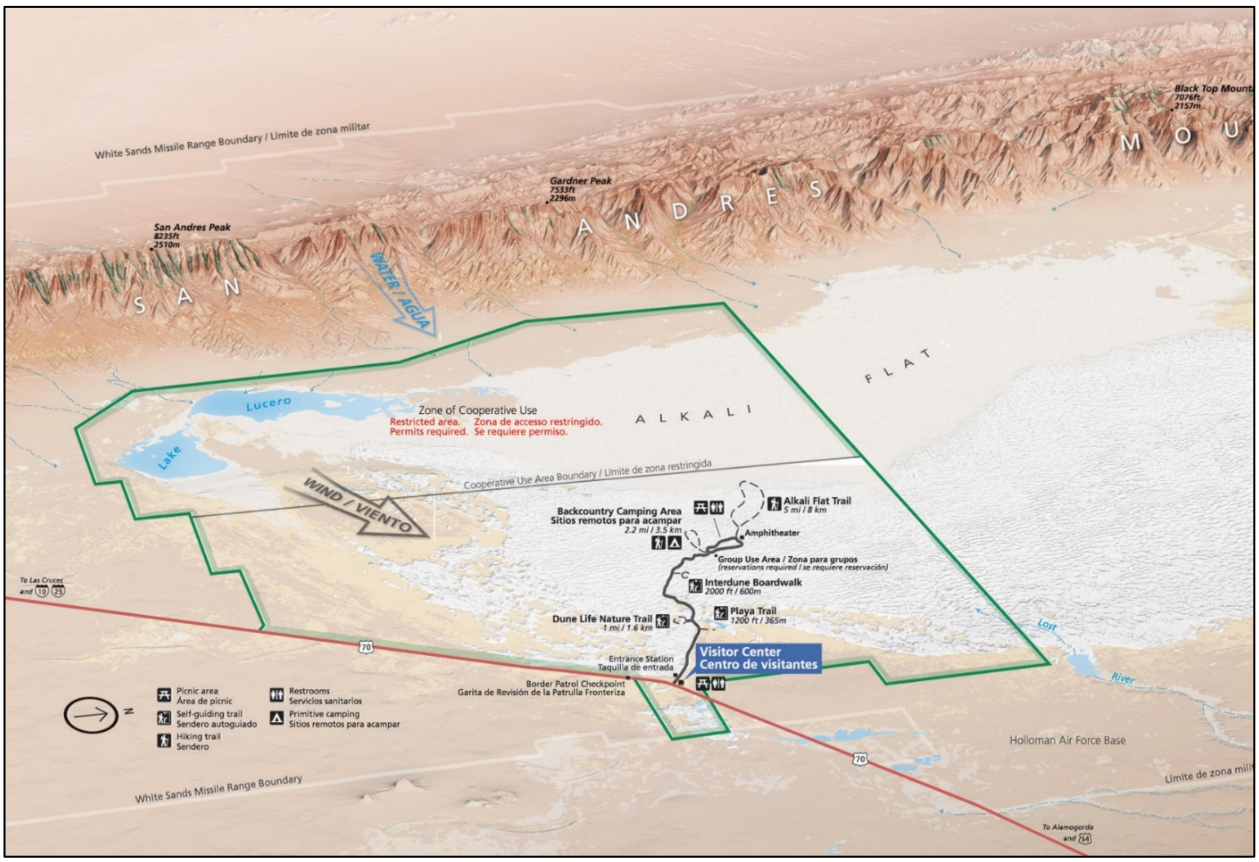

Figure 3. WHSA, located in southern New Mexico's Tularosa Basin, protects 40% of the world's largest gypsum dune field (NPS).

The unique snow-white environment that makes up WHSA is only 10,000 years old but supports a host of remarkable and unique organisms endemic to the profoundly "white" environment of the park (Rosenblum 2006). In addition, the dunes and gypsum-rich sediments preserve thousands of archeological sites and globally unique late-Pleistocene human and giant megafauna fossils (Bustos et al. 2018). At the western edge of the dune field is a large playa that is as unique as the dune field itself. The playa is much older than the dune field and is the origin for the gypsum crystals that break into the fine sands that constitute the dune field. The gypsum-rich sediment of the playa also preserves fossil human and megafauna footprints that are older than the dunes (Bustos et al. 2018). In order to meet stewardship responsibilities, understanding which areas of the system are most susceptible to the stresses of climate change is critical to focus research and monitoring efforts and develop new questions and a deeper understanding of the system.

Nadeau et al. (2017) describe the WHSA dune system as being composed of four dune types, classified according to shape: dome, barchan, transverse, and parabolic (McKee 1966; Fryberger 2001). Dome dunes represent the youngest of the dune formations and occur only on the upwind edge of the dune field. Dome dunes are composed of fine sand, reaching only 3 to 6 ft in height, and lacking a steep face. Dome dunes typically transition to barchan (crescent-shaped) or transverse (straight-lined sand ridges perpendicular to the dominant wind direction) dunes. Transverse barchan dunes occur where the dune formations align together a plane perpendicular to the wind. Parabolic dunes are U-shaped and are formed when the centers of the dunes migrate faster than the horn or arms of the dune (Nadeau et al. 2017). Parabolic dunes are typically older, with vegetation covering a large portion of the sand sheet. When vegetation is destabilized, the unidirectional winds will erode part of the dune, pushing the destabilized section leeward and creating the typical U-shape.

Figure 4 identifies the approximate locations of the four dune formation types found at WHSA. The area identified as the "Zone of Cooperative Use" is land within the park that is also used by the neighboring White Sands Missile Range and does not have public access.

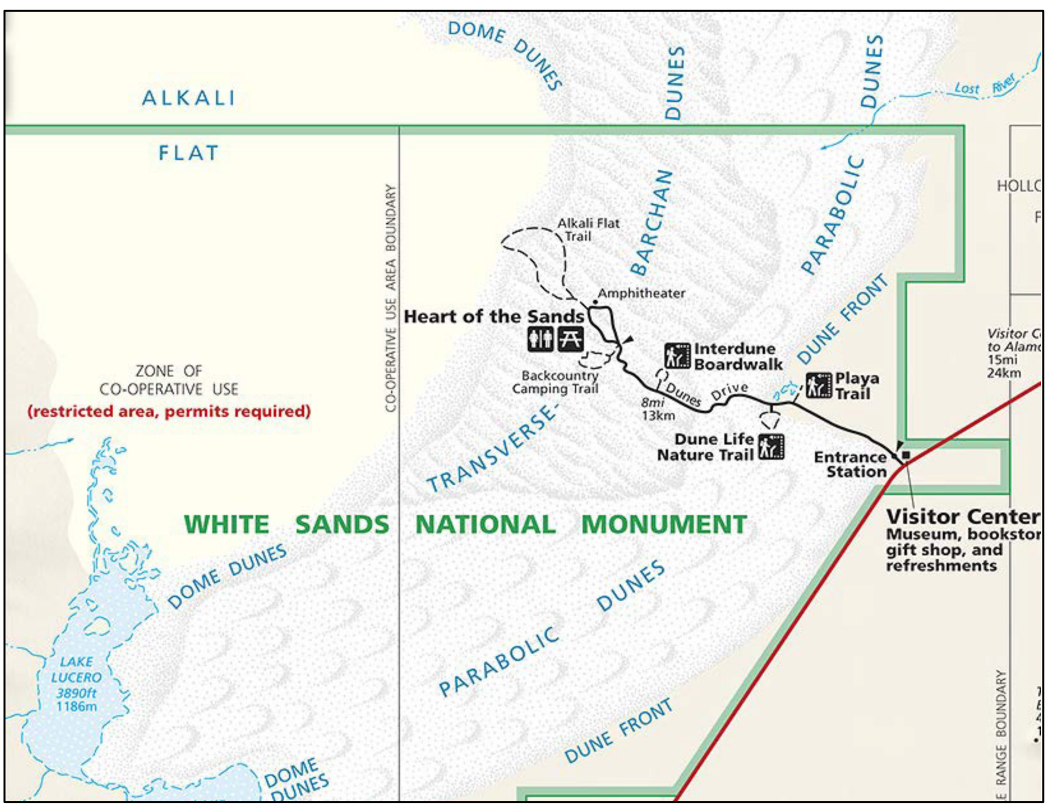

Figure 4. Locations of major dune types at WHSA (NPS).

The White Sands dune field is classified as a wet aeolian system, meaning that the water table depth controls accumulation and migration or erosion of sand material (Fryberger 2001; Kocurek et al. 2007; Nadeau et al. 2017). The water table is typically sufficiently shallow to allow moisture to seep to the surface and stabilize dune sands against wind erosion (Nadeau et al. 2017). When the dunes dry, the gypsum sand may move exponentially (both in amount and the distance transported) with an increase in the wind, creating dramatic dust storms (Figure 5). As local demand for groundwater grows and the impacts of climate change increase, the shallow groundwater table that sustains the dune field and the associated unique biological, paleontological, and archeological assemblages are likely to become increasingly jeopardized.

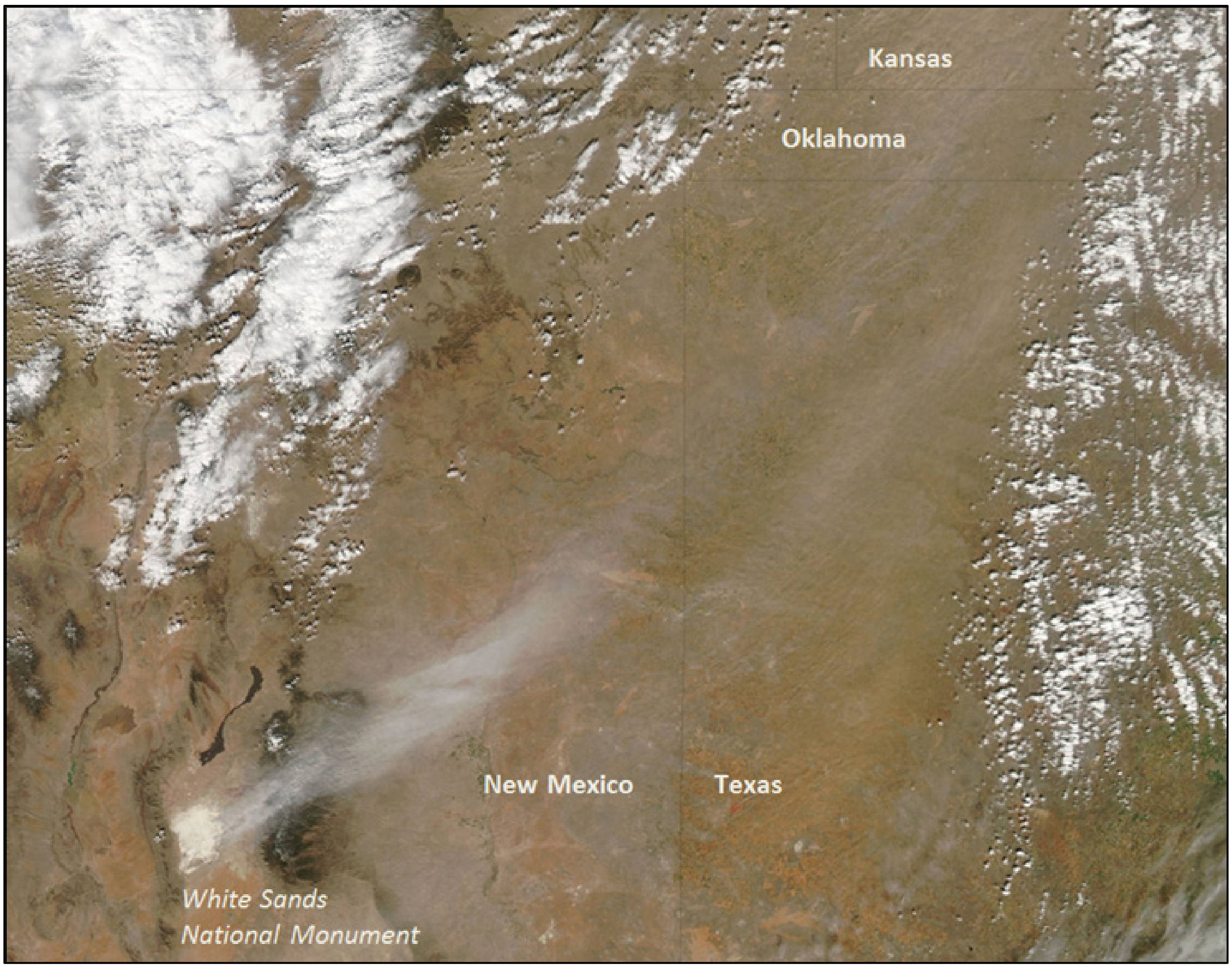

Figure 5. National Aeronautics and Space Administration (NASA) image showing gypsum-sediment particles from the White Sands dune field (center left) blowing into the panhandles of Texas and Oklahoma, February 28, 2012. Predominant prevailing winds across the dune field are southwest-to-northeast like this.

The landscape at WHSA is highly dynamic due to changes in sediment moisture and resulting gain of sand through formation of new crystals and wind-driven loss of dust and sand from the basin. Attributing current changes in the dune system to specific factors (such as climate change or external groundwater withdrawals) relies on understanding the driving factors and the natural range of variability in these processes over past decades. Rachal and Dugas (2009) describe highly variable patterns in the dune field over a 60-year period (1944–2005) suggesting, but not confirming, a trend toward a state of disorganization. A dune modeling protocol developed by Rachal and Dugas (2009) demonstrated that measured parameters, such as dune spacing, do change on decadal time scales, likely in response to external factors such as precipitation and evapotranspiration. Additionally, researchers developed a groundwater model (tied to an existing regional groundwater model) to better understand the effects of groundwater withdrawals versus those of climate change over the next 50 years (Newton and Allen 2014; Bourret 2015). The model showed that regional groundwater, which likely enters the shallow system from the east, is the dominant component in the shallow dune groundwater system. This regional groundwater component has a distinct geochemical signature and is more than 10,000 years old. Increased pumping in Alamogordo, based on this model, will result in water-level decline of up to 4.92 ft for the regional groundwater system near WHSA due to a change in the evapotranspiration rate with continued climatic shifts (Newton and Allen 2014; Bourret 2015). A significant decrease in groundwater levels in the dune aquifer system would likely make much of the existing accumulated sand more available for transport by wind, significantly changing dune dynamics as well as local ecosystems and habitats (Newton and Allen 2014).

Additionally, dynamics intrinsic to the dune field formation itself, such as dune-to-dune interactions, are very common in younger dunes, which tend to show a higher degree of dune migration. In general, dune "pattern" development (i.e., the transition of younger dune types to older dune types) is thought to improve with development time. However, Ewing and Kocurek (2010) noted that there are numerous boundary conditions within each of the differing dune formations in the dune field that control how the dune organizational processes occur over time. For example, pattern organization at WHSA may be complicated by the multiple paleo-shorelines (from Pleistocene Lake Otero), which appear to exert a significant, if not primary, control on these patterns (Ewing and Kocurek 2010). LiDAR surveys and detailed image analyses completed by Kocurek et al. (2012) support the influence of boundary conditions on dune organizational patterns.

The interdunal areas (lower elevation areas between sand dunes) and the older dune formations support most of the vegetation and wildlife found at WHSA. Dominant vegetation communities found at WHSA include desert, semi-desert grasslands, desert scrub, and woodlands (Nadeau et al. 2017). The unique microenvironments created by the various dune formations support a rich diversity of biological organisms. The WHSA natural resource condition assessment report (Nadeau et al. 2017) notes that the national park is home to 289 plant species from 51 families. Vertebrates in WHSA include 1 species of fish, 38 species of reptiles and amphibians, 52 species of mammals, and 238 species of birds. Many plant and animal species have developed highly specialized means of surviving in this area of cold winters and hot summers, with very little surface water and highly mineralized and brackish groundwater. Plants must also be able to withstand the climatic conditions of the Chihuahuan Desert and successfully find sources of fresh water. They have adapted to a constantly shifting landscape by growing fast, reproducing, and sending a new generation forward before they are covered by a passing dune.

The unique white gypsum environment at WHSA has given rise to many endemic species. At the top of the lists are 60 endemic species of moths (Figure 6). According to Metzler (2014, p. 83), “The number of endemic species of moths to White Sands National Park compared to all of North America is the highest for a single location.”

Figure 6. *Euxoa lafantainei* is one of 60 endemic moth species found at WHSA (NPS).

Although the reptiles found at WHSA are typical of the Chihuahuan Desert ecoregion, this unique white ecosystem provides habitat for numerous desert reptile species, including one endemic species, the bleached earless lizard (*Holbrookia maculate ruthveni*) (Figure 7).

Figure 7. The endemic bleached earless lizard (*Holbrookia maculate ruthveni*) (NPS).

Additionally, WHSA has one of the world’s largest concentrations of Ice Age fossils of human and megafauna footprints, which are unique in showing human and megafauna interactions and behavior. For the archeological community, these provided a new form of data not previously available. Fossil prints also occur in the Ice Age Lake Otero, an ephemeral lake that drains a large area on the Sacramento Mountains. Thousands of these prints have been lost to soil erosion as the lake margins continue to dry. Lowering of the water table or soil moisture at WHSA would similarly rapidly accelerate the erosion of these globally significant fossil footprints and associated evidence for human and Pleistocene megafauna interactions (Figures 8 and 9).

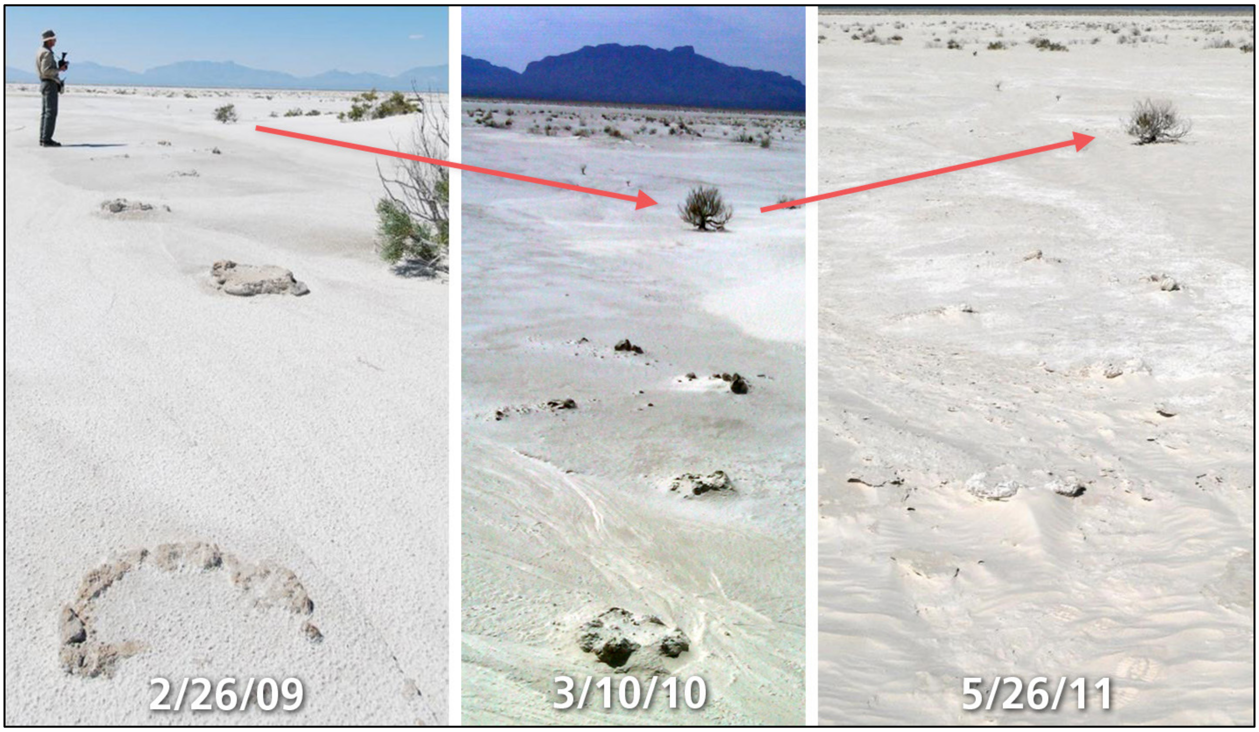

Figure 8. Time series photographs showing the rapid erosion of fossil footprints (NPS).

Figure 9. Documenting and masking ice age animal and human prints before they are lost to erosion (NPS).

Biophysical Systems Drivers

Reiser and Bustos (2014) and the Chihuahuan Desert Inventory and Monitoring Network (Nadeaus et al. 2017) summarized information regarding biophysical drivers at WHSA. Key ecosystem drivers derived from Reiser and Bustros (2014) are provided below.

Precipitation has an indirect influence on dunes through the recharge of groundwater, which in turn is a key driver of dune dynamics (described below). Precipitation also enhances dune moisture, which indurates (hardens/stabilizes) dune sediments and limits the sediment available for wind transport. Precipitation in the dune fields is generally low (8–12 inches), and highly variable in amount and timing among years and seasons. Recharge generally occurs during spring storms and in late summer and early fall with the monsoonal storms (Crabaugh 1994; Langford et al. 2009). Precipitation influences the depth to groundwater and salinity, both of which influence dune stability. In years with high rainfall, dilution of otherwise saline groundwater may partially stabilize active dunes. Periods of high precipitation and recurrent flooding can cause eolian aggradation of the interdunes (Kocurek et al. 2007).

Groundwater hydrology is a key element in creating and maintaining the gypsum dune field in WHSA (Figure 10). Groundwater brines leaching from bedded evaporites are likely an important source of gypsum (McLean 1970; Allmendinger et al. 1973; McLean 1975; Myers 1983; Cruz 1985; Myers and Pinckley 1987; Myers and Sharp 1989, 1992; Basabilvazo et al. 1994; Langford 2003). Evaporation at the surface drives wicking of saline water from the shallow water table, 3–9 ft below the surface (Allmendinger et.al. 1973). Gypsum crystallizes as a powdery efflorescence on the surface and as small crystals at and below the surface but above the water table (Allmendinger et al. 1973). The gypsum, which constitutes the bulk of the extant dunes, was derived from deflationary episodes when large areas of the present-day salt flats were excavated by wind during prolonged droughts. High groundwater salinity decreases dune stability by inhibiting vegetation growth (Langford et al. 2009). Older dunes are vegetated and stable, and portions of WHSA dunes are estimated to have been stable for at least 3,400 years (Langford et al. 2009).

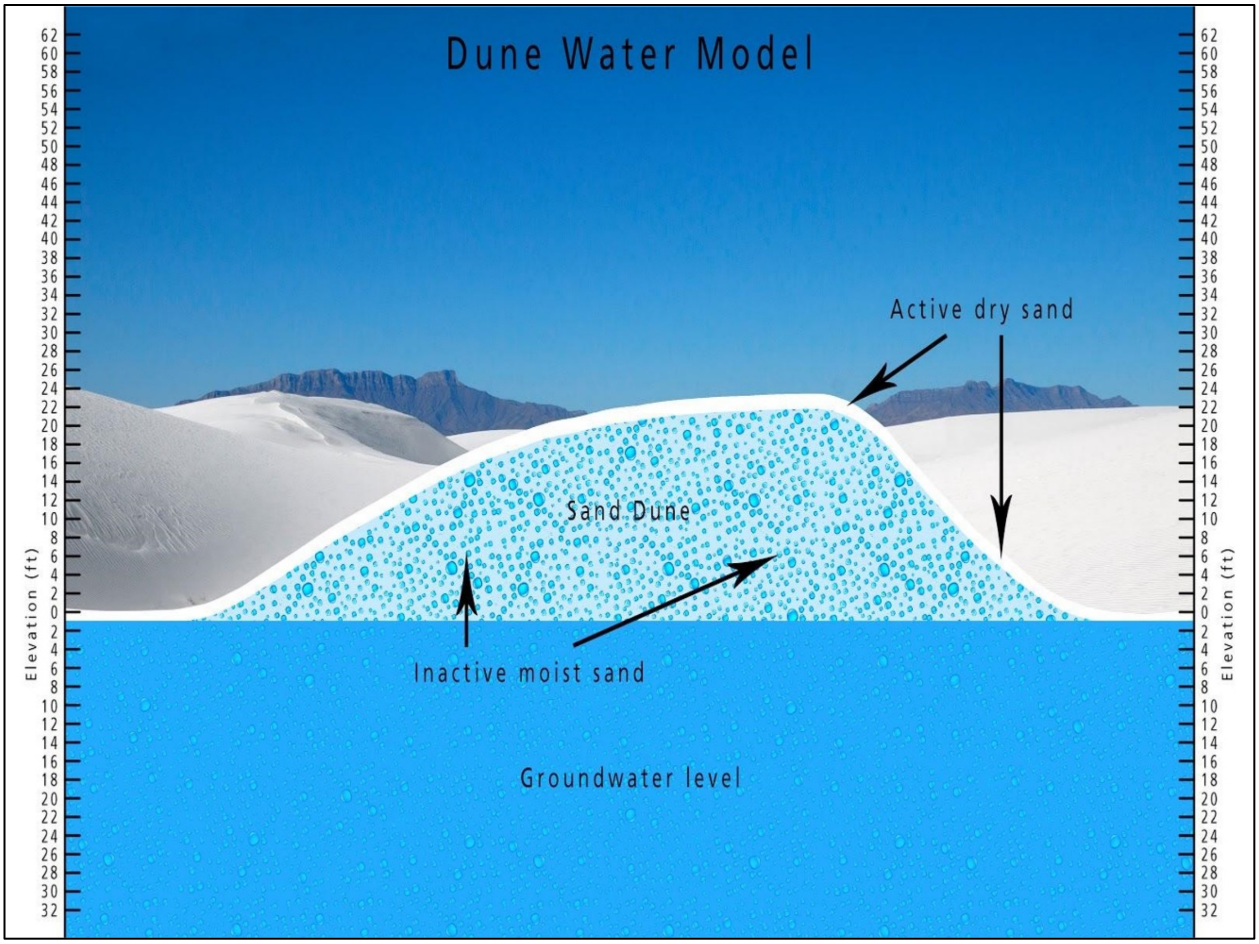

Figure 10. Conceptual model showing relationship between groundwater and moisture wicked up in dune sand by capillary forces (NPS).

More recently, work by Newton and Allen (2014) helped to clarify the role of the local hydrology and dune dynamics, and demonstrated clear linkages between the shallow groundwater table, precipitation, and nearby adjacent systems (specifically Lost River, an ephemeral stream that drains a large area on the Sacramento Mountains). Within the dune field, depth to water in interdunal areas ranges from 1 ft to 3 ft below the surface. Known as a wet dune system, the shallow groundwater beneath this type of dune field directly affects dune processes. Here, groundwater effectively stabilizes sand that has accumulated for thousands of years. At WHSA, up to 30 ft of gypsum sand is stored below interdunal areas. A significant decrease in groundwater levels in the dune aquifer system would likely make much of this accumulated sand more available for transport by wind, significantly changing dune dynamics as well as local ecosystems and habitats (Newton and Allen 2014).

Winds determine the movement of sand across the dune fields (Fryberger and Dean 1979; Frank and Kocurek 1994, 1996; Fryberger 2001). At WHSA, dominant winds from the west-southwest transport sand to the northeast across the dune field. Frank (1994) and Frank and Kocurek (1994, 1996) examined local sand transport and wind velocities across dune elevations and found that sand transport was highest at the tops of the dunes. The parabolic dunes and active dune sand areas migrate on a continuous basis, and extreme wind events accelerate their movement. The parabolic interdunes and vegetated dune areas are stable and sufficiently vegetated such that extreme wind events result in little to no dune movement.

Floods and droughts can dramatically change dunes. If floodwaters remain fresh or brackish, they may result in expansion of vegetation within interdunes and the stabilization of migrating dunes (Langford et al. 2009). On the other hand, if the fresh water mixes with saline groundwater and becomes toxic for the local vegetation, then vegetation may be lost and dunes may migrate (Langford et al. 2009). Extended droughts may have the most significant impacts. The geologic record shows that the various parts of the dune field formed rapidly during short hyper-arid events. A prolonged and significant drop and subsequent loss of available water may result in mobilization of the parabolic interdunes and other areas that are currently stable in the park.

At WHSA, Quaternary and Holocene landforms are responsible for the current distribution of dunes (Fryberger 2001). The older dunes currently occupy a topographic high point that was an island in a lake that covered the landscape between 38,000 and 12,000 years ago (Seager et al. 1987; Fryberger 2001). The main dune field now occupies what was the lake floor at that time. This pluvial lake (i.e., a basin in which drought periods exceed wet periods), Lake Otero, formed under a cooler and wetter climate where inflow from the surrounding mountains exceeded outflow to the groundwater. The dune fields of WHSA currently migrate across a stepped landscape, where ancient shorelines mark the steps. These steps also mark changes in groundwater salinity (Langford et al. 2009), sulfur isotopes (Szynkiewicz et al. 2009), and dune morphology (Kocurek et al. 2007; Langford et al 2009).

White Sands National Park Dune System Model

Several models depict various drivers, influences, and potential response affecting the dune systems of WHSA. Developed for the Chihuahuan Desert Inventory and Monitoring Network, the Dune Ecosystem Characterization Model (Figure 11) provided a framework for workshop participants to consider potential system changes and vulnerabilities.

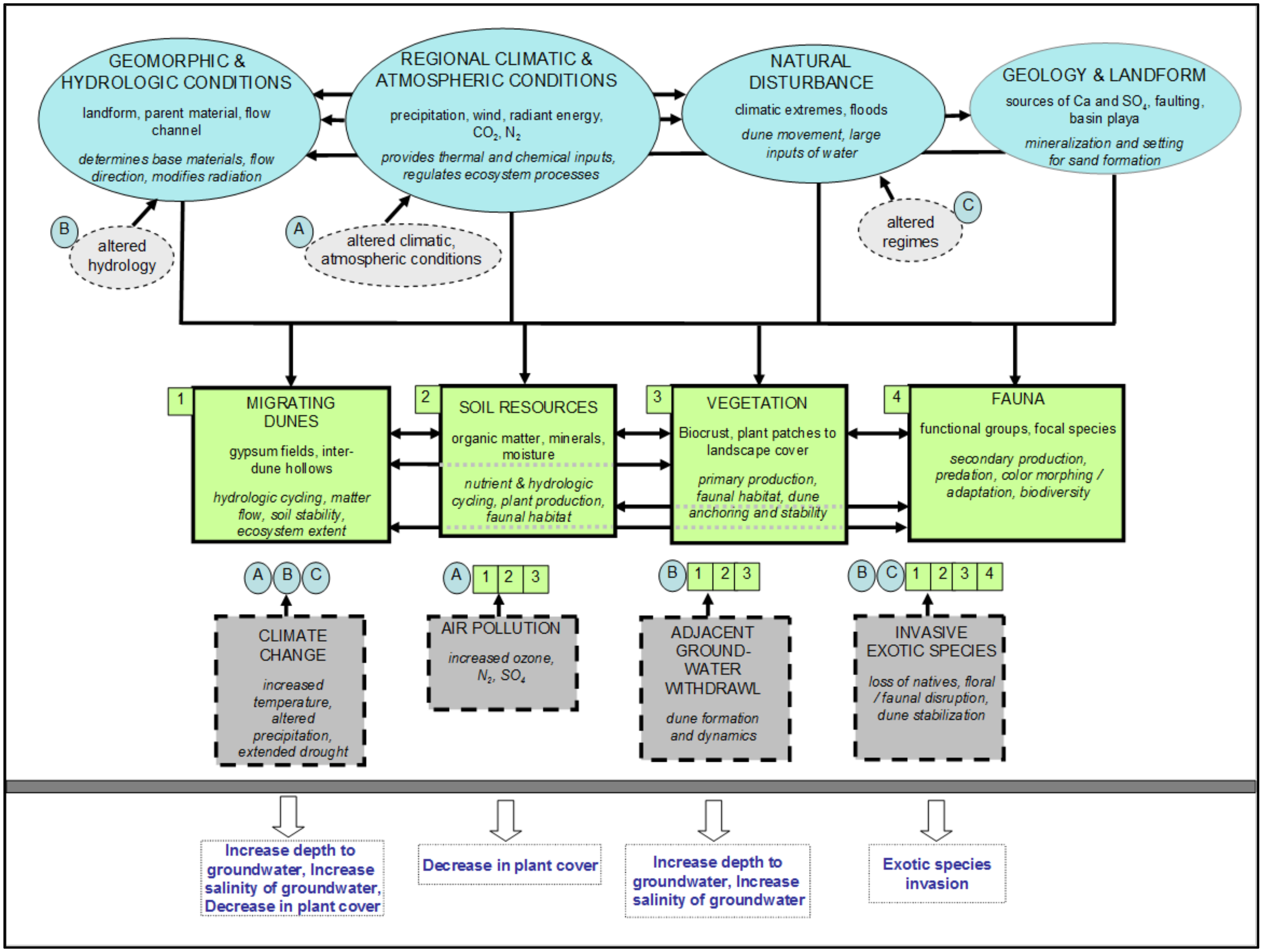

Figure 11. Ecosystem characterization model for the CHDN dune ecosystem. Solid ovals are drivers and interactive controls. Solid rectangles are system components that are interactive controls. Dashed rectangles are stressors, and dotted rectangles with blue text are key degradation processes associated with each stressor (NPS 2010).

Key Degradation Processes for Resources at White Sands National Park

The unique biophysical systems at WHSA are highly sensitive to change. Four key degradation processes are projected to negatively impact dune ecosystems at WHSA (Table 1) (Reiser and Bustos 2014). Climate change, groundwater withdrawal on adjacent lands, and exotic plants will increase the salinity and change depth of groundwater. Temperature and moisture-induced stress under climatic shifts may lead to higher plant mortality in this xeric system. Climate change will intensify these degradation processes with the potential to significantly affect stability of the dune systems found in the park.

Table 1. Key degradation processes in the dune ecosystem, stressors, and impacts associated with these processes, and potential measures to characterize these processes and effects (Reiser and Bustos 2014).

Degradation Process	Stressor	Impacts	Potential Measures
Increase depth to groundwater	Climate change, exotic plant invasion, groundwater withdrawn on adjacent lands	Altered soil-water dynamics leading to decrease in dune stability	Groundwater quantity and quality measures, land use related to water extraction on adjacent lands, abundance of exotic species, climatic elements
Increase salinity of groundwater	Climate change, exotic plant invasion, groundwater withdrawn on adjacent lands	Altered soil-water dynamics leading to decrease in dune stability	Groundwater quantity and quality measures, land use related to water extraction on adjacent lands, abundance of exotic species, climatic elements
Exotic species invasion (plants)	Exotic plant invasion	Altered soil-water dynamics leading to decrease in dune stability, increase in dune stability where water table is unaffected, shift in functional-group structure	Vegetation composition and structure, climatic and atmospheric elements
Decrease in plant cover	Climate change, air pollution	Altered soil stabilization properties leading to decrease in dune stability, altered biotic integrity with decrease in plant cover	Vegetation composition and structure, climatic and atmospheric elements

Climate Change Scenarios for White Sands National Park

Management-relevant climate-resource scenarios use projected changes in resource-relevant aspects of climate, assess projected changes against historical climate and weather events, and describe potential consequences of plausible future climates for focal resources in the context of other stressors. The WHSA workshop used a refined, qualitative scenario planning approach focused on expert opinion and synthesis of pre-existing science.

The yellow square in Figure 12 is the downscaled Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al. 2012) grid cell used for analysis of climate at WHSA. The Coupled Model Intercomparison Project is a collaborative framework designed to improve knowledge of climate change. CMIP5 is a completed phase of the CMIP project (2010–2014) that improves understanding of climate and provides estimates of future climate change. Input data included daily 1/8-degree (~8-mi) gridded climate data, downscaled using bias-corrected constructed analog (BCCA) process originally developed by the US Bureau of Reclamation (2013). This analysis used forty global climate models (GCMs) for each of two greenhouse gas emission pathways (known as representative concentration pathways [RCPs])—RCP 4.5 and RCP 8.5. Emissions in RCP 4.5 peak around 2040 and then decline. Emissions in RCP 8.5 continue to rise throughout the 21st century.

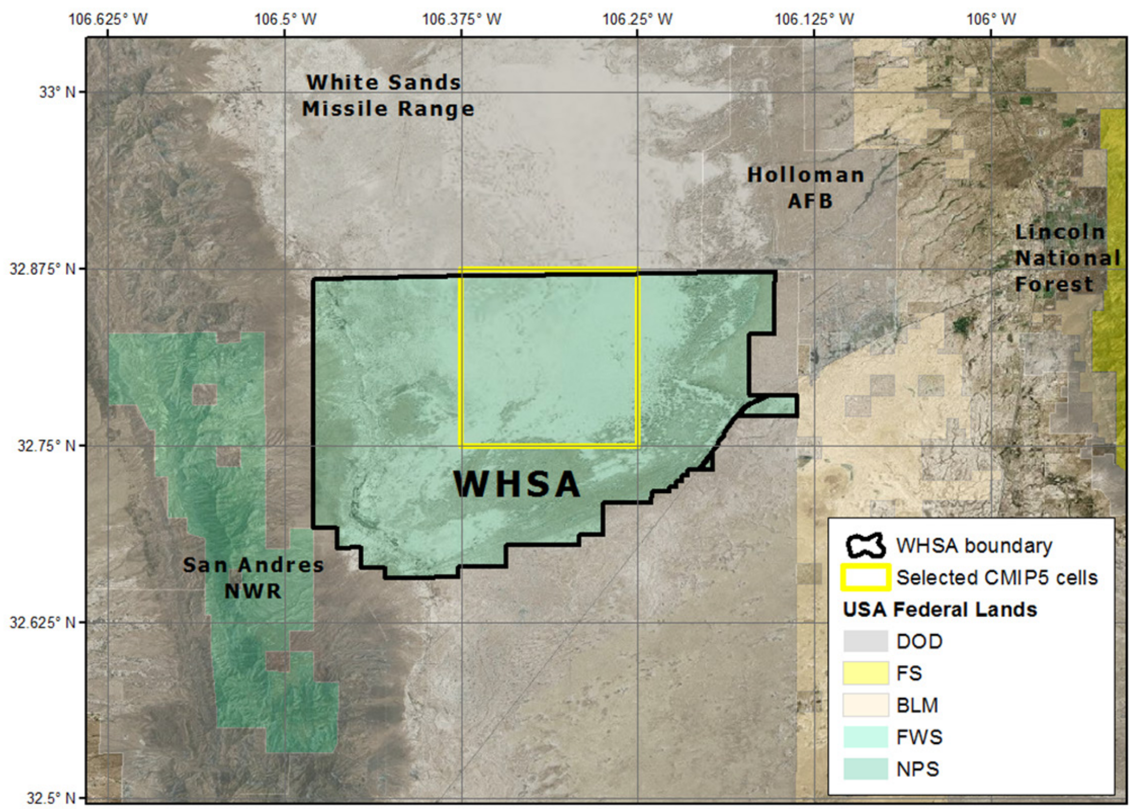

Figure 12. Map of WHSA and surrounding area. The yellow square is the downscaled Coupled Model Intercomparison Project phase 5 (CMIP5) grid cell used for this analysis of climate, which includes the park's centroid.

Climate Futures for White Sands National Park

Our exploration of the projections focused on comparisons of means calculated from future (2025–2055) and historical (1950–1999) periods for each metric. Three plausible, divergent climate futures were developed specifically for WHSA (and the associated Tularosa Basin). A climate future is a summary of output from a single projection (i.e., a single GCM run for a given representative concentration pathway) and is therefore temporally and physically coherent and plausible. The climate futures focus on climate metrics that are relevant to park resources and to which people can easily relate. Three climate futures were sufficient to bound the range of ways that climate could change in this area. This suite of climate futures represents scientifically plausible alternative climate pathways that could occur in the coming decades. Climate futures establish the fundamental structure of climate-resource scenarios (Runyon et al. 2020) and must illustrate four key characteristics of useful scenarios for resource management: *plausibility, relevance,* and *divergence* sufficient to *challenge* existing assumptions about the way in which the future may unfold. This sets the foundation to guide forward-looking resource management (NPS 2013). The climate futures were defined based on projected changes in average annual temperature and total annual precipitation (Figure 13), aspects of climate to which WHSA resources are sensitive. Potential future conditions are characterized in terms of change relative to the historical period of 1950–1999.

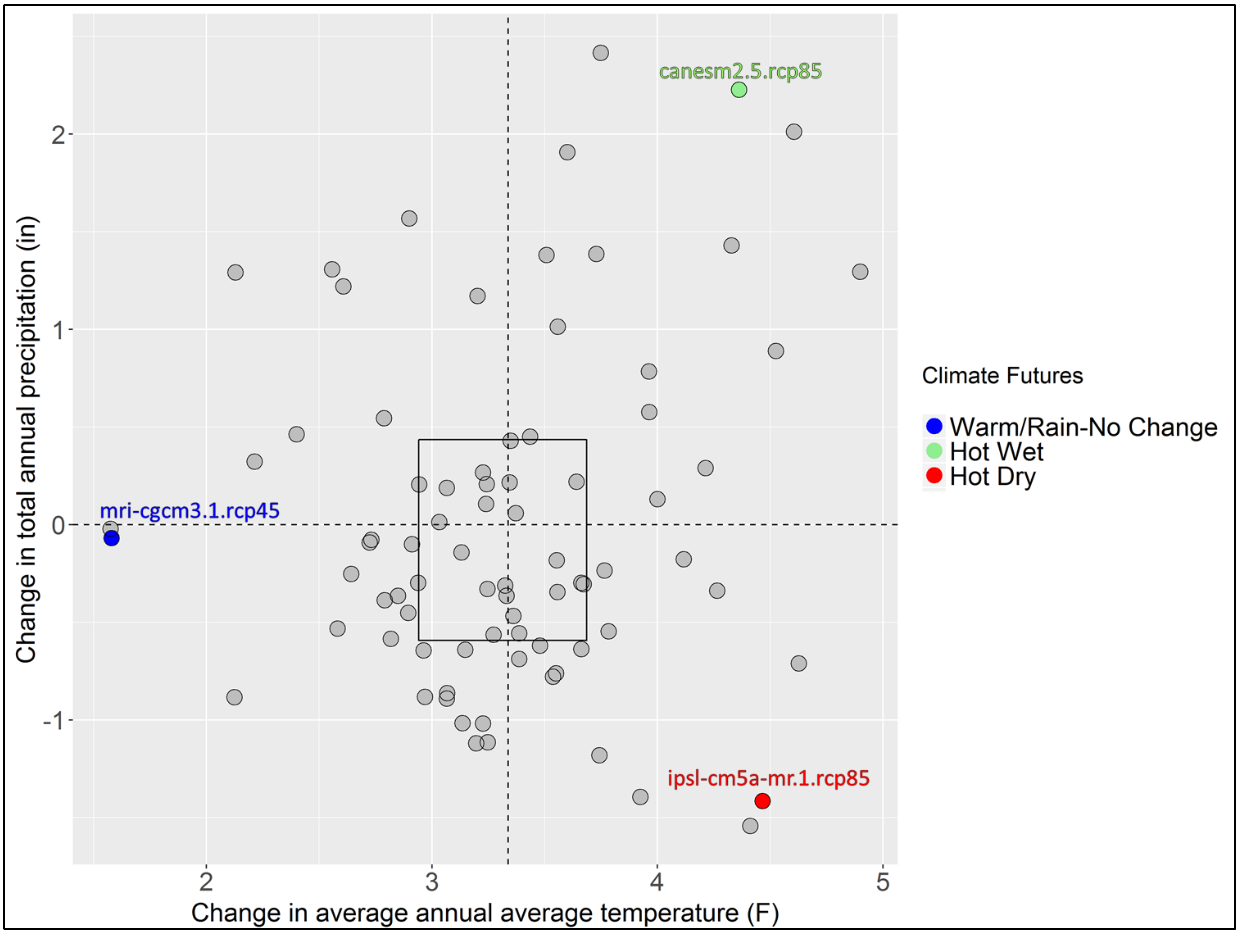

Figure 13. The three climate futures (i.e., GCM-RCP combinations) for WHSA (blue circle: MRI-CGCM3.1.rcp85, green circle: canesm2.5.rcp85, red circle: IPSL-CM5A-MR.1.rcp85), chosen to maximize divergence in terms of change in annual precipitation and annual average temperature for the 30-year period centered on 2040, relative to the historical period (1950–1999). Data are from two simulations each of 40 downscaled CMIP5 GCMs for WHSA. Each model was run with a moderate (RCP 4.5) and high greenhouse gas emissions pathway (RCP 8.5) most consistent with current trends. Dashed lines indicate the median value for each axis and the box indicates a central tendency, which is those models inside of the 25th and 75th percentiles for each of the axes. Grey GCM/RCP combinations are projections that were not considered for climate future selection. Colored GCM/RCP combinations are projections selected for climate futures. The specific GCM projections chosen for climate futures are MRI-CGCM3.1.rcp45[1], CanESM2.5.rcp85[2], and IPSL-CM5A-MR.1_rcp85[3]. Circle color corresponds with the color of the climate futures and scenarios used throughout this document.

[1] The name "MRI-CGCM3.1.rcp45" is shown highlighted in blue just before the footnote marker. This note is provided to help people with low vision, or that otherwise cannot read the word with that background color behind it, read that sentence properly.

[2] The name "CanESM2.5rcp85" is shown highlighted in green just before the footnote marker. This note is provided to help people with low vision, or that otherwise cannot read the word with that background color behind it, read that sentence properly.

[3] The name "IPSL-CM5A-MR.1_rcp85" is shown highlighted in red just before the footnote marker. This note is provided to help people with low vision, or that otherwise cannot read the word with that background color behind it, read that sentence properly.

White Sands National Park Climate Futures (2025–2055) – Synopses

- **Climate Future 1 – Warm/No Precipitation Change**[4]
  - Warming low (average annual temperature increases 1.5 degrees Fahrenheit [°F])
  - >100°F 26 days/year (6-day increase)
  - Annual precipitation: no change
  - Water balance: annual climatic deficit (potential evapotranspiration [PET] minus actual evaporation [AET]) increases by 7.5%
- **Climate Future 2 – Hot and Wet**[5]
  - Warming severe (average annual temperature increases 4.1°F)
  - >100°F 36 days/year (16-day increase)
  - Annual precipitation: 2-in increase (27%); change concentrated in July and August
  - Water balance: annual climatic deficit (potential evapotranspiration minus actual evaporation) increases 12.7%
- **Climate Future 3 – Hot and Dry**[6]
  - Warming severe (average annual temperature increases 4.1°F)
  - >100°F 42 days/year (22-day increase)
  - Annual precipitation: 1.5-in decrease (−17%); change distributed evenly June–December
  - Water balance: Annual climatic deficit (PET-AET) increases by 26.5%

Figures 14 through 17 provide graphical representation of these three climate futures compared to historical conditions. Factors common to all three of these climate futures include warming in all seasons, a roughly 50% decline in days <32°F (Figure 15), and an increase in water deficit ranging from 7.5 to 26.5% (Figure 17). Note that data presented are all mean conditions, around which there will be substantial year-to-year variation.

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[4] The phrase "Climate Future 1 – Warm/No Precipitation Change" is shown in blue text just before the footnote marker. This note is provided to help people with low vision, or that otherwise cannot read the word with that font color applied, read that sentence properly.

[5] The phrase "Climate Future 2 – Hot and Wet" is shown in green text just before the footnote marker. This note is provided to help people with low vision, or that otherwise cannot read the word with that font color applied, read that sentence properly.

[6] The phrase "Climate Future 3 – Hot and Dry" is shown in red text just before the footnote marker. This note is provided to help people with low vision, or that otherwise cannot read the word with that font color applied, read that sentence properly.

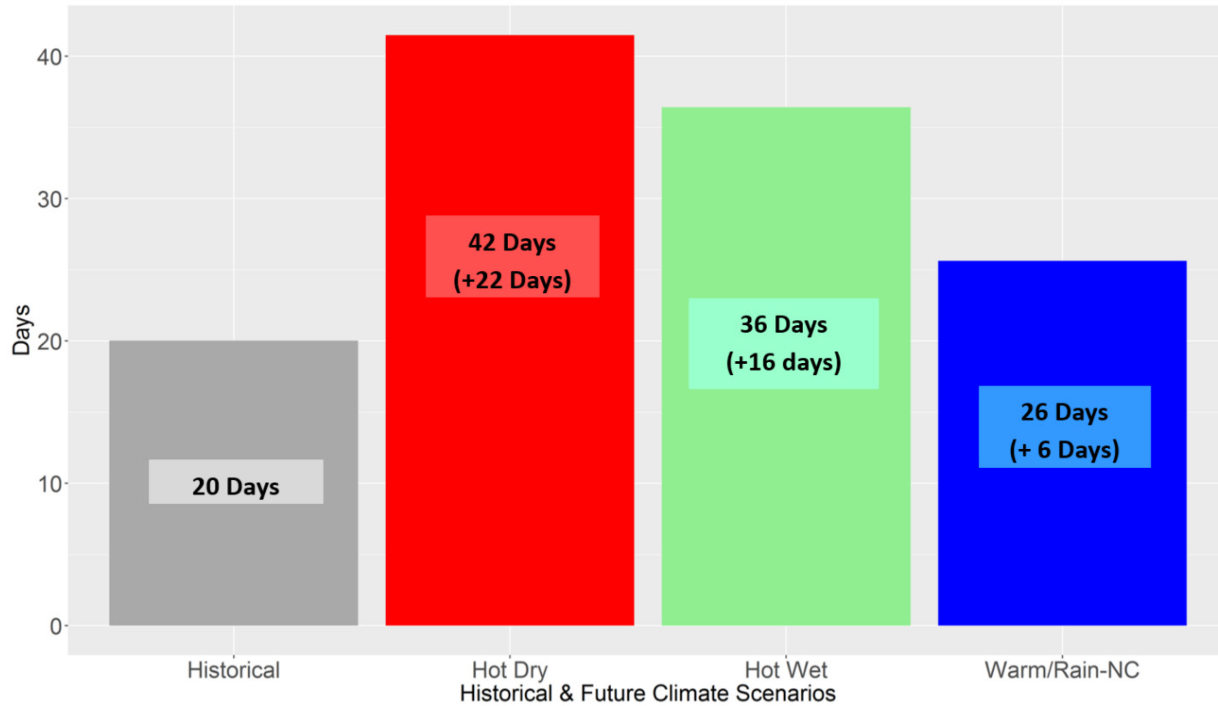

Figure 14. Comparison of average total days/year >100°F based on historical conditions (1950–1999) and for 2025–2055 under three selected climate futures developed for WHSA.

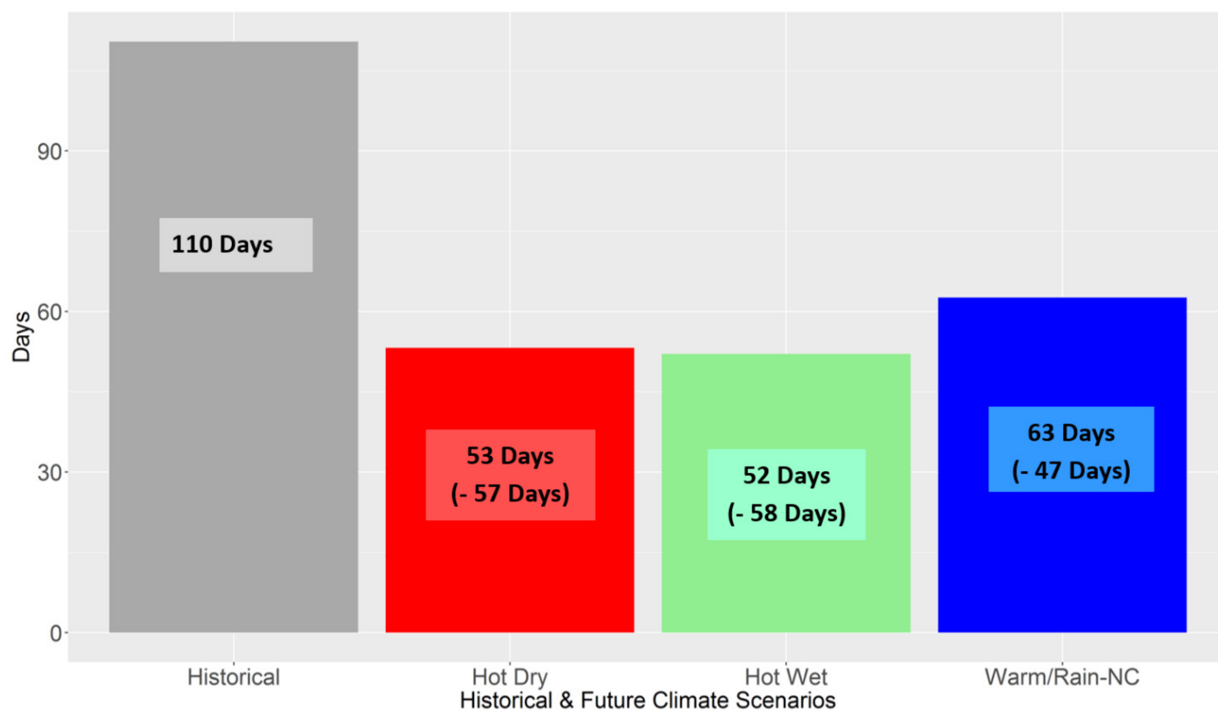

Figure 15. Comparison of average total days/year <32°F based on historical conditions (1950–1999) and for 2025–2055 under the three climate futures developed for WHSA.

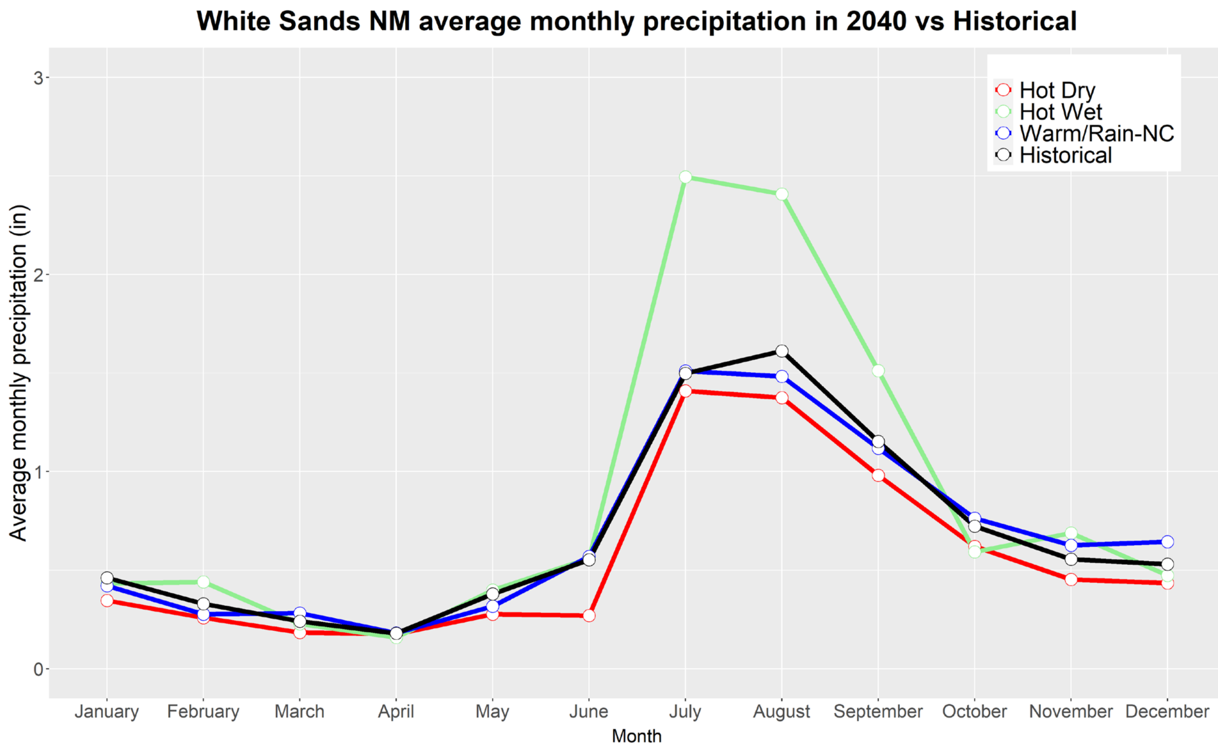

Figure 16. Long-term average monthly precipitation for the historical period (1950–1999) and for 2025–2055 under the three climate futures developed for WHSA.

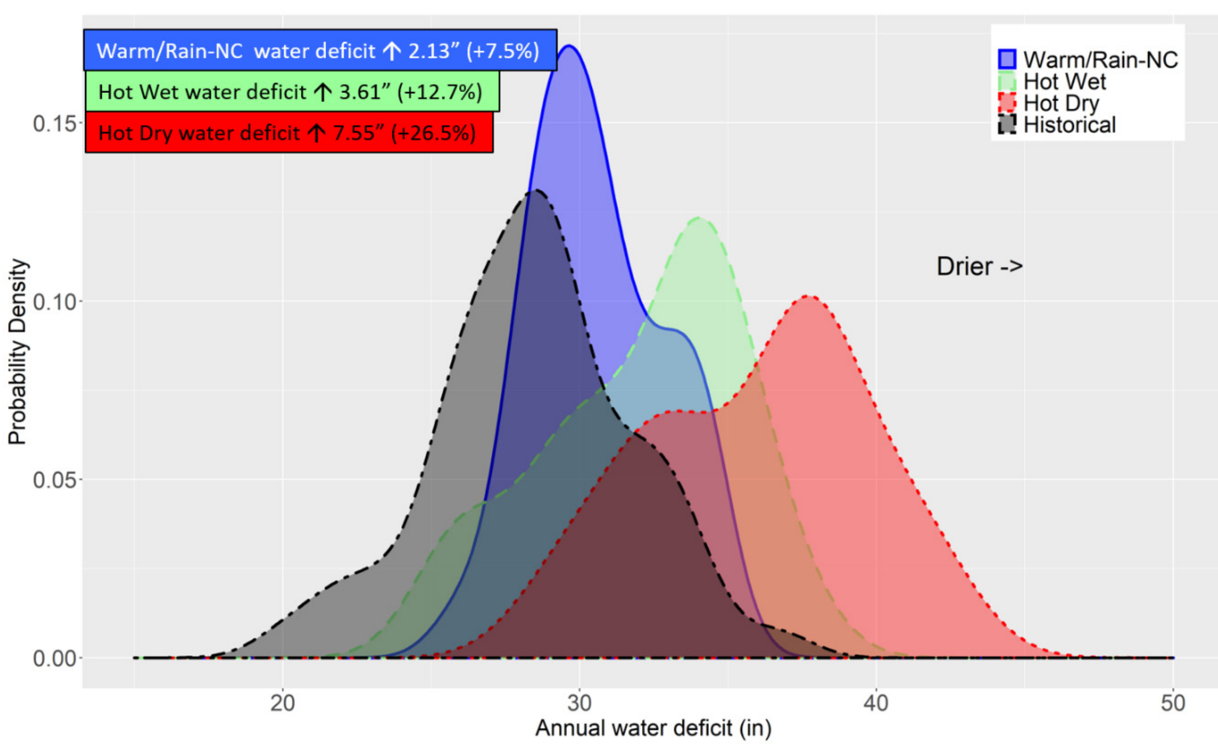

Figure 17. Comparison of annual climatic water deficit for WHSA for the historical period (1950–1999) and for 2025–2055 under the three climate futures developed for WHSA. Water balance model courtesy of David Thoma (NPS).

Figure 14 shows a comparison of average total days/year >100°F based on historical conditions (1950–1999) and under the three selected climate futures (2025–2055) for WHSA. Compared to the historical average of 20 days/year above 100°F, the park could experience a 30% to 110% increase. Figure 15 provides a comparison of the average total days/year <32°F based on historical conditions (1950–1999) and for 2040 under the three climate futures developed for WHSA. Based on the modeled results, the park may see a decrease in the number of days below freezing ranging between 47% (Hot/Wet climate future) and 57% (Warm/No Precipitation Change climate future). Figure 16 identifies long-term average monthly precipitation under historical conditions (1950–1999) and for the three climate futures (2025–2055). Average monthly precipitation under the Warm/No Precipitation Change climate future (blue line) shows very little change from historical average precipitation (black). Under the Hot/Wet climate future (green line) there is an expected increase of 2 in of precipitation above the historical average, with the most notable change concentrated in the mid- to late summer where precipitation could increase by approximately 50%. Average monthly precipitation under the Hot/Dry climate future (red line) shows a reduction in annual precipitation by approximately 1.5 in, with the reductions fairly equally distributed across the second half of the year.

Water balance modeling for WHSA based on historical conditions (1950–1999) and for the three selected climate futures (2025–2055) is perhaps the most significant for understanding potential changes because of the importance of groundwater to WHSA ecosystems (Figure 17). All three of the selected climate futures for WHSA would result in an increase in the annual climatic water deficit (i.e., drier conditions), ranging from an increase of 7.5% (Warm/No Precipitation Change) to 26.5% (Hot and Dry climate future) over the historical condition. The climatic water deficit, potential evapotranspiration minus actual evaporation, is a measure of the amount of additional water that would have been evaporated or transpired had it been present in the soil, given temperature forcing (see Appendix B for additional water balance information).

Climate Change Scenario Planning Implications for Future Research

The 1-day scenario planning workshop focused on a researcher audience because their knowledge was critical both for developing climate futures into climate-resource scenarios that could guide resource management and for identifying critical uncertainties regarding resource vulnerabilities. Presentations on key scientific topics and management issues were provided to give context and baseline information for the workshop participants. The workshop began with a brief presentation by Davis Bustos (WHSA Resource Management Chief) to provide an (1) introduction to WHSA, (2) update on the development of the park's research corridor, and (3) overview of the structure and goals for the climate change scenario planning workshop. Cheryl Mcintyre (NPS, CHDN Ecologist) presented information on the conceptual Dune Ecosystem Model (Figure 10, NPS 2010) developed by the NPS Chihuahuan Desert Inventory and Monitoring Network. Dave Dubois (New Mexico State Climatologist) provided an overview on climate and climate trends for the Tularosa Basin. Gregor Schuurman (NPS, Climate Change Response Program [CCRP] Ecologist; Figure 18) served as the facilitator for the workshop and provided presentations on (1) how climate change-informed science can support resource management and (2) climate change projections and implications for the Tularosa Basin, including methods used to develop the three climate futures for use by workshop participants to identify vulnerabilities and potential impacts to key park resources. Appendix A lists all workshop participants and their respective affiliations.

Figure 18. Gregor Schuurman, NPS Climate Change Ecologist, facilitated the WHSA Scenario Planning Workshop (NPS).

Working individually for approximately 15 minutes using pre-printed worksheets (Figure 19), participants examined the implications of each climate future on resources represented by their own area of expertise. For each of the three climate scenarios, the worksheet specifically asked each technical expert to (a) identify the specific ecosystem component for which he/she possessed relevant expertise, (b) characterize the likely resource response to the scenario, (c) define the mechanism behind the expected resource response, (d) determine the level of certainty about the expected resource response, and (e) identify source(s) of uncertainty regarding resource response(s). An example of the pre-printed worksheets is provided in Appendix C.

Figure 19. Workshop participants fill out worksheets (NPS).

After participants completed initial responses to the requested worksheet information, each provided a short presentation on hypothesized resource responses, coupled with a group discussion to further flesh out details (Figure 20). Table 2 presents a brief overview of the hypothesized ecosystem component responses to each of the three climate futures for WHSA, with a more detailed summary of expert thoughts on resource responses shown in Appendix D.

Figure 20. Workshop participants discuss potential resource impacts under three climate futures (NPS).

Table 2. Hypothesized resource responses to climate futures for WHSA.* Table F-1 is a more accessible version of this same table that is designed specifically to be easier to read by screen reading software for people with certain visual and cognitive impairments; or with low vision, various types of color-blindness, or cannot read the text against some of the table cell background colors used.

Ecosystem Component	Warm and No Precipitation Change	Hot and Wet	Hot and Dry
Geomorphic & Hydrological Systems	Blue ↔	◌ (empty, dashed)	Yellow ↓
Dust Emissions	Yellow ↓	Yellow ↑	Yellow ↓
Playa Sand Source	Blue ↑	Yellow ↑	Yellow ↓
Biocrust – Coarse Resolution	Blue ↓	Blue ↓	Blue ↓
Gypsum-Endemic Plants	Blue ↔	Red ↓	Red ↓
Endothermic Vertebrates	Yellow ↔	Blue ↓	Blue ↓
Desert Bighorn Sheep	Yellow ↔	Yellow ↔	Blue ↓
Lepidoptera *spp*.	Yellow ↑	Yellow ↑	Blue ↓
Arthropods	Yellow ↔	Blue ↑	Blue ↓
Nematodes	Yellow ↓	Red ↑	Red ↓

* Horizontal arrows identify no change or minimal change from current condition, Down arrows identify negative response, and up arrows identify positive response. Empty, dashed circle identifies uncertain or unknown. Blue arrows represent a LOW level of certainty; Yellow arrows represent a MEDIUM level of certainty; Red arrows represents a HIGH level of certainty.

All three of the climate futures would involve some level of change to at least half of the resources examined, based on current information available and the professional opinion of subject-matter experts present at the workshop (nearly all resources would be impacted under the two warmer climate futures). The least amount of potential negative/adverse impact to resources would likely occur under the “Warm and No Precipitation Change” climate future (closest to current climatic conditions), but the levels of certainty identified by subject experts were predominantly low or medium due to identified needs for additional research/information. Certainty levels for resource responses were more mixed under the “Hot and Wet” and “Hot and Dry” climate futures. These two climate futures represent significant deviations from current/historical conditions, which allowed experts to feel more confident about their identified potential resource impacts, again with the caveat that additional research would better inform potential resource responses. Even though there could be some positive (i.e., desirable) responses by some taxa under the “Hot and Wet” climate future, experts noted that there would likely be changes in the actual species composition compared to the current conditions. Similarly, the “Hot and Wet” climate future could also assist to minimize excessive dust emissions. The “Hot and Dry” climate future would likely create the most significant level of change and would represent the greatest adverse responses to all resources examined, including unique endemic species to the park (Figure 21).

Figure 21. Female bleached earless lizards (*Holbrookia maculate ruthveni*) occur in WHSA and are bright pink and orange during breeding season (NPS).

Understanding Resource Vulnerabilities and Identifying Key Research Next Steps to Support Climate Change Adaptation at White Sands National Park

Understanding and responding to resource vulnerabilities in the face of uncertain change will be critical for effective management of resources at WHSA. Specifically, increasing the park's understanding of (1) "***which*** species or systems are likely to be most affected by projected changes" and (2) "***why*** these key resources are likely vulnerable" (see Glick et al. 2011) will help identify appropriate adaptation strategies and actions. Glick et al. (2011) identified the key components of vulnerability (Figure 22).

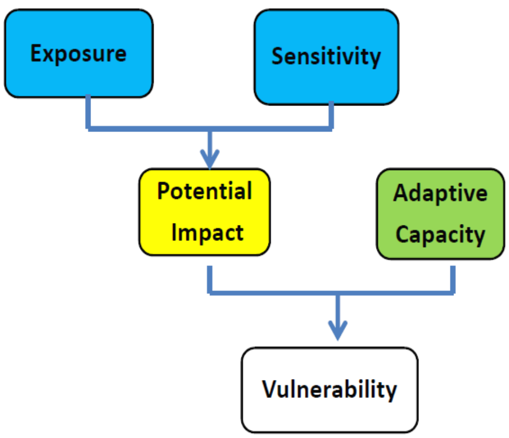

Figure 22. Key components of vulnerability, illustrating the relationship among exposure, sensitivity, and adaptive capacity (Glick et al. 2011).

The three climatic futures presented to workshop participants provided a preliminary step to begin to understand possible exposure scenarios for park resources. Through expert opinions and knowledge of existing science, participants assessed the likely sensitivity and adaptive capacity of the discussed resources (i.e., how vulnerable would resources be under the conditions of each of the three identified futures?). Workshop participants identified the level of certainty they had in defining their postulated resource impacts.

Based on the three climate futures examined for WHSA (higher temperatures with precipitation conditions that will not overcome expected levels of temperature increase), participants concluded that temperatures and climatic water deficit will likely increase at WHSA. These changes, in combination with expected increases in evaporation rates, have the potential to significantly affect soil moisture levels. Even if annual precipitation levels continue to increase, alteration to the timing and/or intensity (i.e., extreme rain events) of precipitation events intermixed with prolonged periods of drought may result in a drop in the water table and associated dune moisture levels. This could result in the mobilization of the parabolic interdunes in addition to other areas that are stable under the current climatic conditions (NPS 2010).

Additionally, WHSA is close to several localities that depend on the limited surface water and groundwater features for their drinking water (Bourret 2015). Resource managers at WHSA are concerned that the projected changes in regional climate due to climate change, coupled with the expected increased pumping pressure on groundwater resources for drinking water supplies, will adversely affect the shallow aquifer that supports the dune field (NPS 2010; Bourret 2015). However, because there are over 175 mi^2 of dunes, workshop participants felt it likely that even under the worst-case scenario, sand would be present for hundreds and possibly thousands of years. Some habitat types may be lost, along with some endemic and/or more specialized species, but it is also likely that many species will adapt and persist.

Workshop participants—scientists and managers with a history of working together to understand the park's resources and foster effective resource management—discussed their scenario-based characterizations of vulnerabilities in depth and then carefully evaluated this collective understanding in the context of the park's resource management needs (Figure 23). They pinpointed critical information gaps that hinder more effective climate change adaptation in this geologically unique and ecologically complex environment. Specific research needs differ among resource types, although most resources share a need to fill data gaps for lesser understood species/ecosystem components. However, participants also identified an important higher-level research-related need associated with supporting holistic climate change-informed management: better integration of research efforts among the different scientific disciplines. Specifically, participants called for efforts to more strongly connect and share information among the various research groups/disciplines (e.g., via additional workshops and webinars).

Table 3 represents some of the preliminary ideas provided by workshop participants on the types of research/actions needed to better understand climate change impacts to resources and/or to increase the level of certainty on potential resource vulnerabilities at WHSA. A more complete representation of participant responses can be found in Appendix E.

Figure 23. WHSA Scenario Planning Workshop. Participants reflect on their characterizations of resource vulnerabilities and associated uncertainties to identify key research next steps to support climate change adaptation at WHSA (NPS).

Table 3. Examples of some workshop participant-identified research needed to better understand resource vulnerabilities at WHSA.

Research Need/Data Gaps	Vegetation (Gypsum-Endemic Plants)	Endothermic Vertebrates	Soil Microbial Biocrusts	Arthropods	Nematodes	Dust Emissions	Disciplines That Should Work Together in Developing and Conducting Identified Research
Baseline Inventory and Food Web Assessments	–	–	X	–	–	–	Lichenologist, bryologist, biocrust specialist, geomorphologist, geologist
Species Interrelationships [1]Correlations or associations between plant/animal demographics [2]Correlations between nematode communities, gypsum-endemic plants, and soil microbial biocrusts [3]Arthropod – vegetation relationships	X	X	X	X	X	–	[1]Plant ecologist, animal ecologist, soil ecologist [2]Soil microbial biocrust specialist, nematode specialist, gypsum-endemic plant specialist [3]Plant ecologist, arthropod ecologist, hydrologist, soil scientist
Habitat Requirements, Niche Modeling [1]For soil microbial biocrusts [2]Research specific to vegetation, endothermic vertebrates, arthropods, and nematodes	X	X	X	X	X	–	[1]Lichenologist, bryologist, biocrust specialist, soil scientist [2]Discipline-specific specialist for each identified resource type
Population Dynamics	X	X	–	X	X	–	Discipline-specific specialist for each identified resource type
Physiological Sensitivities	X	X	–	–	–	–	Physiological ecologist (animal and plant)
Genetics, Systematics, Plasticity	X	–	–	–	–	–	Botanist, evolutionary biologist
Physical Processes [1]Enhance shallow aquifer characterization and better understand processes that generate gypsum sand and dust [2]How abiotic environment affects vegetation and arthropods	X	–	X	X	–	X	[1]Hydrologist, geochemist [2]Soil scientist, hydrologist, plant ecologist, arthropod ecologist

Adaptation and Next Steps

The WHSA Scenario Planning Workshop assembled a diverse set of researchers closely associated with the park to characterize and consider potential vulnerabilities and/or impacts to key park resources. This process use a range of plausible climatic futures and characterized not just potential dune field impacts but also uncertainty associated with those determinations. The impacts-assessment process was qualitative, allowing workshop participants and park managers to provide expert opinion and to explore the "what if…?" aspects of the identified scenarios (NPS 2013).

Workshop outcomes includes identification of several areas where more research could improve baseline knowledge of key resources (e.g., life histories, demographics) and enhance the certainty levels associated with potential resource vulnerabilities. A critical takeaway for workshop participants was that future research should more strongly integrate disciplines to better advance our understanding of the ecological complexities of the unique processes, environments, and species found at the park. Participants then specifically identified which disciples they thought should work more closely together to address each uncertainty. Equally important to workshop participants was the unanimous feeling that enhancing communications among researchers through integrated meetings and/or routine workshops would greatly benefit their ability to advance the knowledge base needed to allow park managers to make more informed management decisions using an adaptive and "climate-smart" approach.

Stein et al. (2014) developed a useful framework to guide adaptation planning efforts (Figure 24). This framework clarifies that *adaptation is an on-going process and not a specific product or one-time event*. Additional key concepts identified for adaptation planning include

1.) act with intentionality (link actions to climate change impacts)
2.) integrate adaptation into existing work
3.) reconsider goals, not just strategies (conservation goals change over time and resource managers must make sure that they are embracing forward-looking goals).

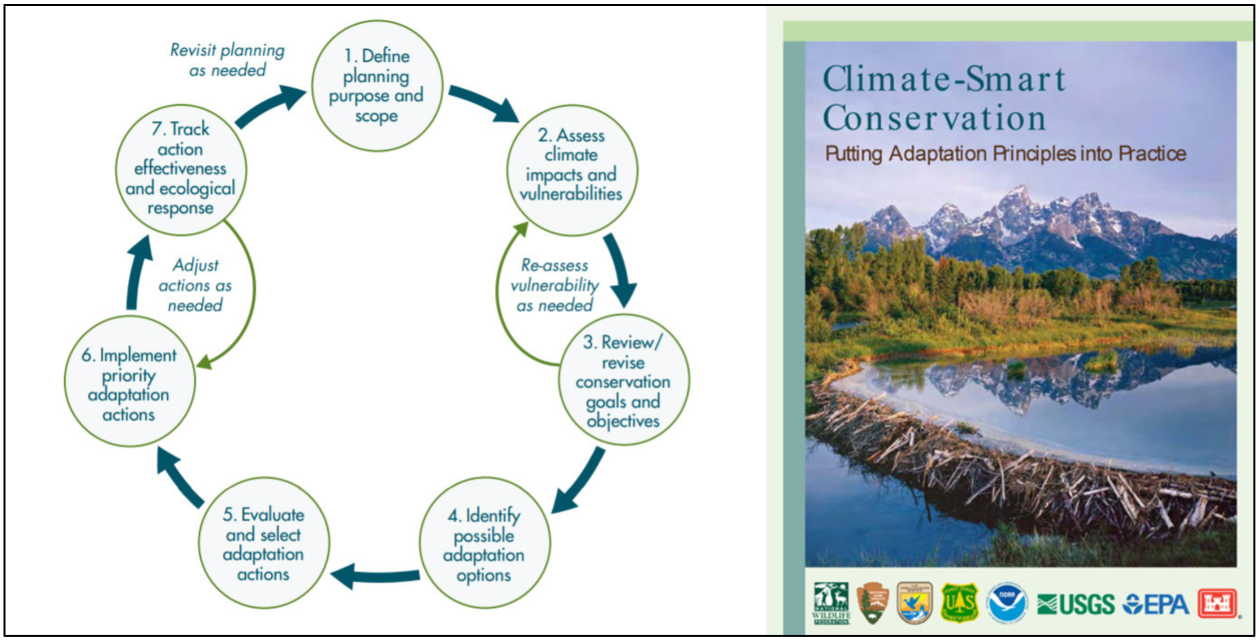

Figure 24. Adaptation framework by Stein et al. 2014.

Inevitably, as climate change progresses, the ability of resource managers to manage resources to maintain their natural condition (i.e., "the condition of resources that would occur in the absence of human dominance over the landscape" NPS 2006) will substantially decline, with the acknowledgement that the future will not look like the past. Understanding the range of plausible climate futures and the vulnerabilities of resources under potential climate scenarios is fundamental for resource managers to identify viable adaptation strategies (Schuurman et al. 2019; Runyon et al. 2020).

The WHSA Scenario Planning Workshop allowed the park and researchers to engage with the first two steps associated with the Climate-Smart Conservation Framework using a set of plausible climate futures. Continued research and enhanced understanding of resource vulnerabilities will allow the park to move forward in defining the most beneficial adaptation strategies and actions. Inevitably, changing climatic conditions will alter the condition of many of the resources found at WHSA. However, continued engagement among current and future park researchers and managers to more completely develop a Climate-Smart Adaptation Framework will provide park managers with the greatest ability to minimize potential adverse impacts and to set (and re-assess) the most appropriate short- and long-term resource management goals.

Post Workshop Accomplishments

Since the workshop, the park consulted with USGS staff to measure water seepage in the playa and lakes and to develop and install a real-time hydrological monitoring network (Figures 25 through 27). The data gathered will support research and monitoring activities highlighted in this report. In addition, the remotely gathered data will augment two dune monitoring protocols (dune movement and dune sediment moisture) developed by the NPS Chihuahuan Desert Network Inventory and Monitoring Program.

Specifically, the instruments placed throughout the dunes and in the alkali flats will help park managers understand the relationships between sediment erosion, dune movement, and changes in vegetation. The groundwater data loggers will assist the park in assessing the conductivity between the regional local aquifer and how it is influenced by sediment moisture, sediment loading, and new gypsum-crystal production. Finally, a series of weather stations (to be installed) will gather climate data and an evaporation tower will measure the loss of sediment moisture, further defining the conditions that form gypsum salts and new salinity crystals.

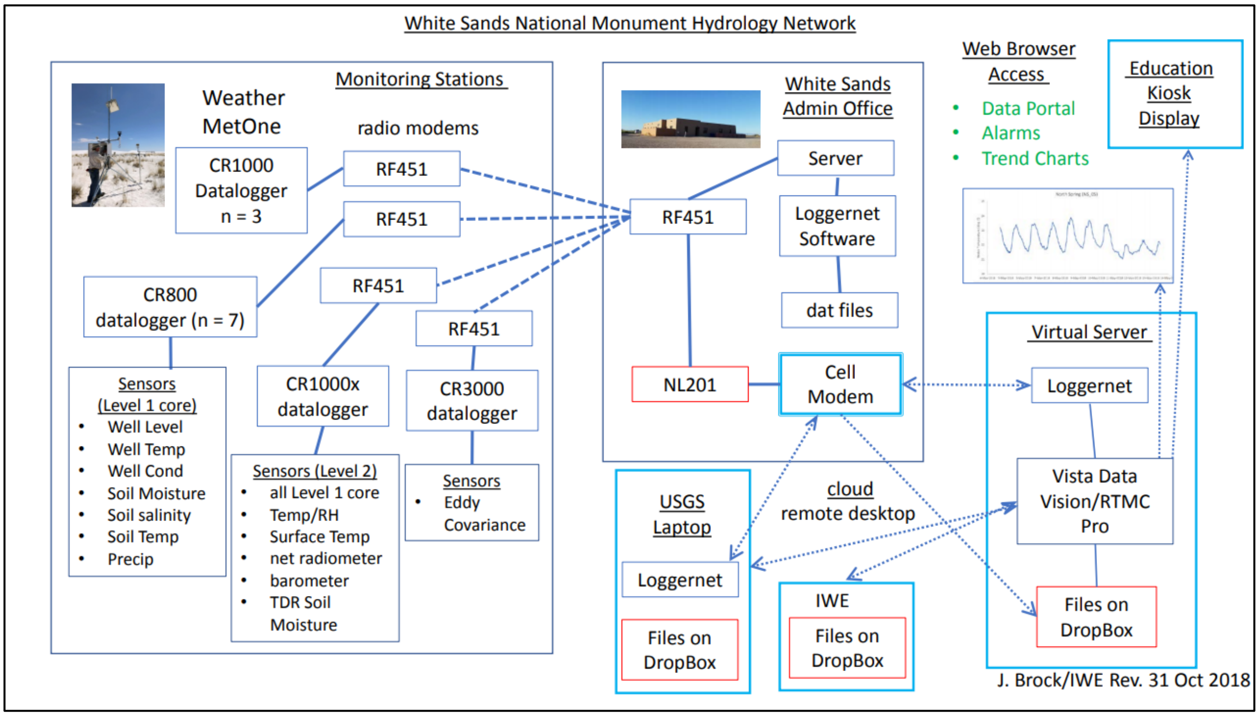

Figure 25. Schematic of WHSA real-time hydrology monitoring network.

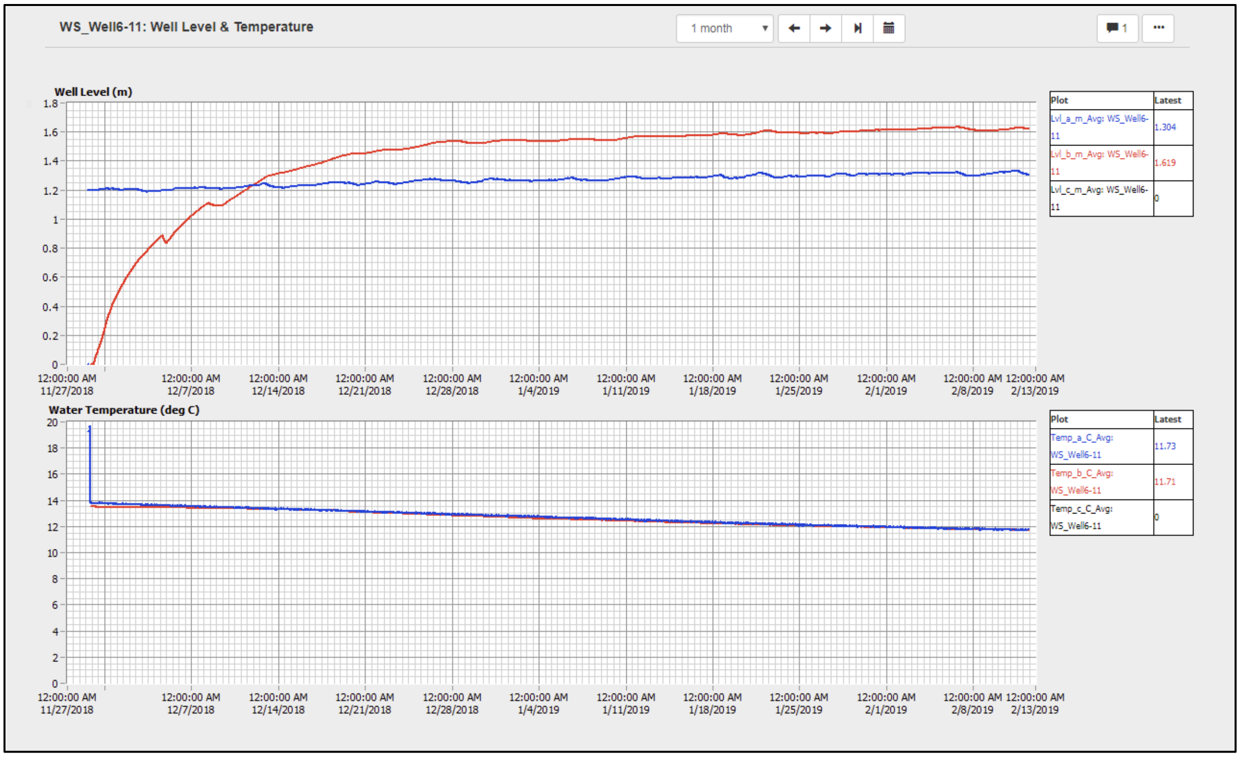

Figure 26. Example of real-time groundwater data taken at WHSA from late November 2018 through February 2019.

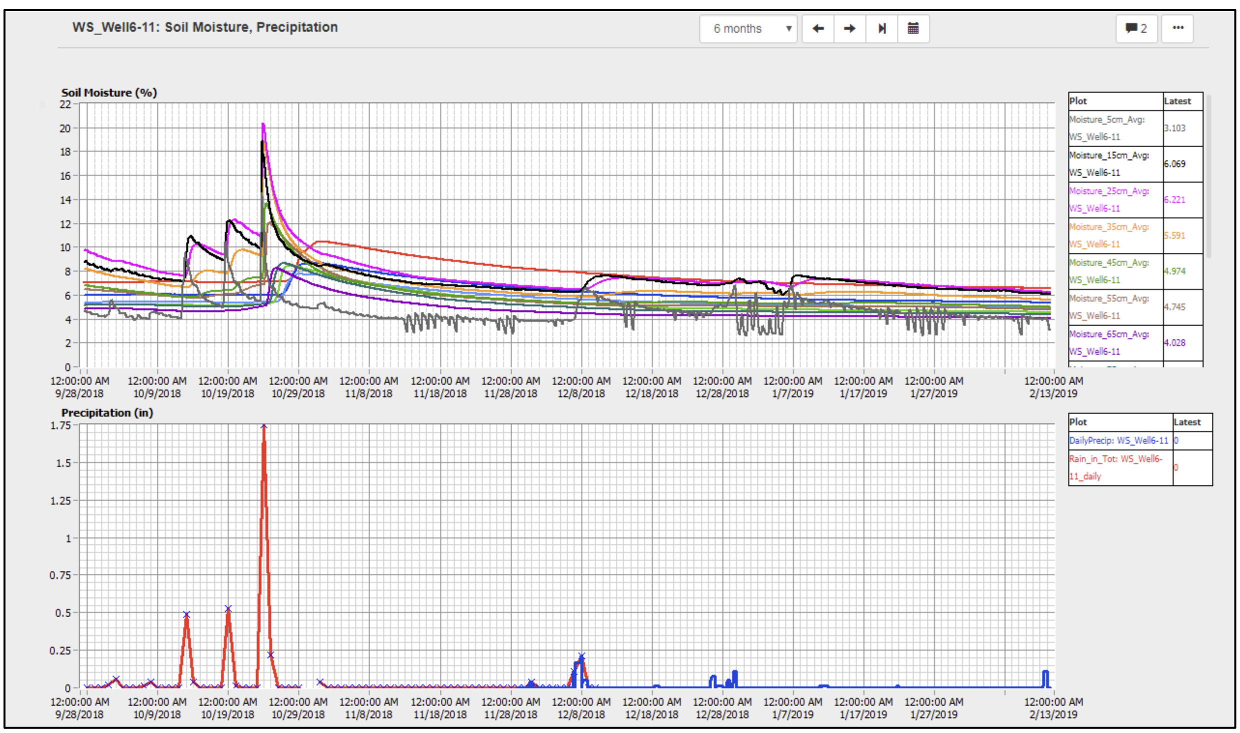

Figure 27. Example of real-time sediment monitoring (sediment moisture, salinity, and temperature) at WHSA from September 2018 through early February 2019.

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Appendix A. White Sands National Park Scenario Planning Workshop – List of Participants

Table A-1. Workshop participants.

Name	Organization	Telephone	Email	Area of Expertise
David Lightfoot	UNM	505.277.4225	dlightfo@unm.edu	Arthropods
Ryan Ewing	Texas A&M	–	rue@tamu.edu	Dune geomorphology
Richard "Rip" Langford	UTEP Geology Department	915.747.5501	langford@geo.utep.edu	Dune geomorphology
Douglas Jerolmack	U Penn	215.746.2823	sediment@sas.upenn.edu	Dune geomorphology
Gary Kocurrk	UT Austin	–	garyk@jsg.utexas.edu	Dune geomorphology
Tom Gill	UTEP Geology Department	–	tegill@utep.edu	Dust
Erica Rosenblum	Berkeley	510.508.2622	rosenblum@berkeley.edu	Evolutionary biology/lizards
Don Weeks	NPS	–	don_weeks@nps.gov	Geology
Bruce Allen	NM Bureau of Geology	–	allenb@nmbg.nmt.edu	Geology
Dave Love	NM Bureau of Geology	–	davel@nmbg.nmt	Geology
Talon Newton	NM Bureau of Geology	–	talon@nmbg.nmt	Hydrology
Paula Cutillo	NPS Hydrologist	–	paula_cutillo@nps.gov	Hydrology
Colleen Filippone	NPS Hydrologist	–	colleen_filippone@nps.gov	Hydrology
Gary Roemer	NMSU	575.646.3394	groemer@nmsu.edu	Mammals
Patrick Mathis	NMGF	575.532.2100	patrick.mathis@state.nm.us	NMDGF habitat specialist
Vincent Santucci	NPS	703.289.2531	vincent_santucci@nps.gov	Paleontology
Colleen Cadwell	NMSU	–	ccaldwel@ad.nmsu.edu	Pupfish
Mara Weisenberger	USFWS/BLM	–	mweisenberger@blm.gov	San Andreas NWR biologist (prior position)
John Gahr	USFWS	575.382.5047 ext. 102	john_gahr@fws.gov	San Andreas NWR manager
Nicole Pietrasiak	NMSU	–	npietras@nmsu.edu	Soil crust
Stephen Thomas	NMSU	–	stthomas@nmsu.edu	Soil nematology

Table A-1 (continued). Workshop participants.

Name	Organization	Telephone	Email	Area of Expertise
Stan Engle	NMSU	–	sengle@nmsu.edu	Water
Joshua Schroeder	WSMR	–	joshua.j.schroeder8.civ@mail.mil	Weather/climate monitoring
Dave Dubois	NMSU	–	dwdubois@nmsu.edu	Weather/climate monitoring
Tom Schmugge	WRRI/NMSU	–	–	Weather/climate monitoring
Caitriana Steele	SW Regional Climate Hub/NMSU	–	caiti@nmsu.edu	Weather/climate monitoring
Antonio Arredundo	NMSU	–	aarredon@cs.nmsu.edu	Weather/ climate monitoring
Pam Benjamin	IMR/NPS Landscape Conservation and Climate Change	–	pamela_benjamin@nps.gov	Weather/climate monitoring
Patrick Morrow	WSMR	–	patrick.c.morrow.civ@mail.mil	Wildlife
Joanna M. Nield	University of Southampton	–	J.Nield@soton.ac.uk	Aeolian geomorphology
Marcia Wilson	CHDN I&M	–	marcia_wilson@nps.gov	Chihuahuan Desert I&M Network Program Manager

Appendix B. Water Balance Modeling Details

Water balance modeling was conducted (using a model developed by David Thoma, National Park Service [NPS]) to analyze how temperature and precipitation interact with site characteristics throughout White Sands National Park (WHSA) to influence water availability. The model uses characteristics (coordinates, slope, aspect, soil type, water-holding capacity) from three random sites, located throughout WHSA (Figure B.1).

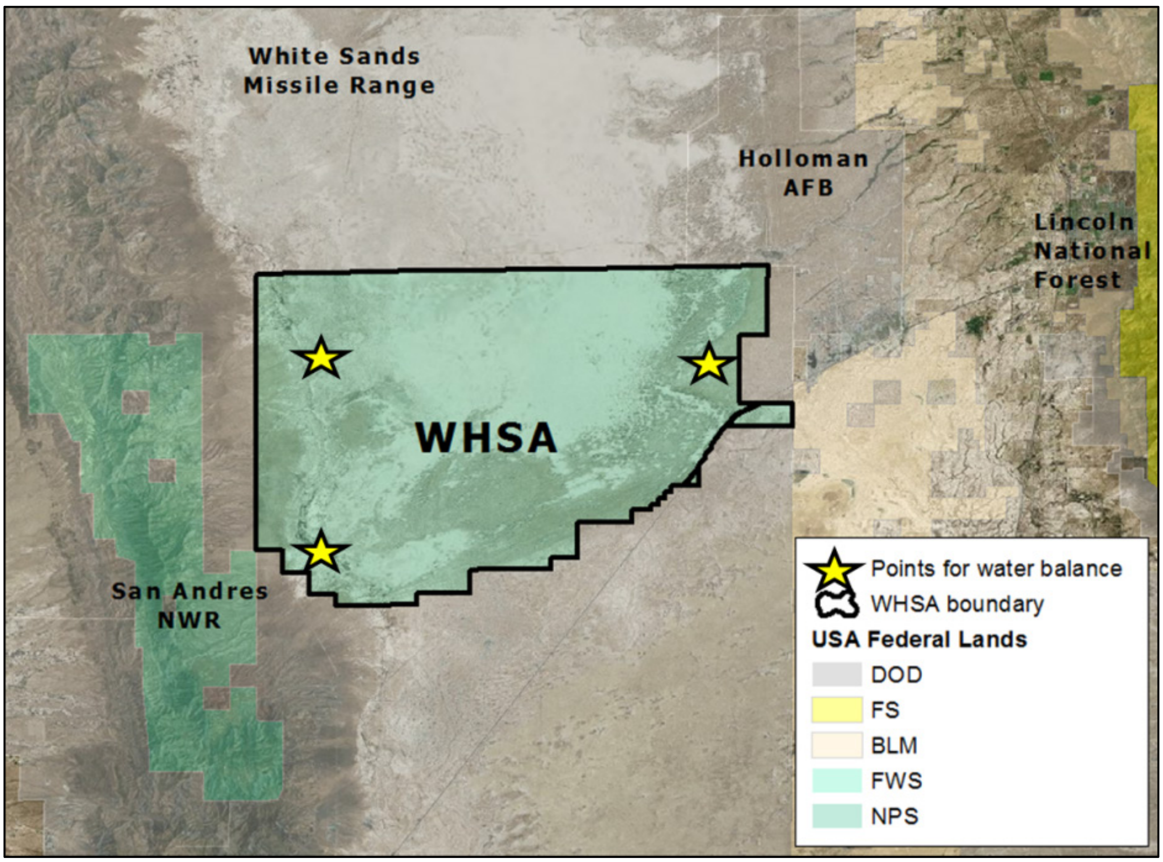

Figure B.1. Randomly selected WHSA sites used for water-balance modeling.

Potential evapotranspiration (PET) was calculated using the Thornthwaite (1948) method, which estimates water loss (given temperature) from evapotranspiration, if water is not limiting. From PET, the climatic water balance (Stephenson 1998) is calculated by estimating the actual amount that is extracted from the soil (actual evaporation [AET]), taking into account soil moisture, soil type, slope, aspect, and precipitation. Climatic water deficit is an estimate of drought stress on soils and plants and can be interpreted as the amount of additional water that would have evaporated or transpired had it been present in the soils, given temperature experienced. Thus, higher values demonstrate insufficient water in the system to evaporate or transpire. Figure 17 (in main document) illustrates the distribution of annual climatic water deficit, showing that under all climate futures the average year will have a greater climatic deficit. The wettest years under the Hot Dry and Hot Wet climate futures will be similar to the driest years experienced historically. Figure B.2, which shows the mean monthly climatic water deficit, reveals decreased water availability for all climate futures, particularly during late spring / early summer, a period when seasonal winds may have a greater effect on dune transport.

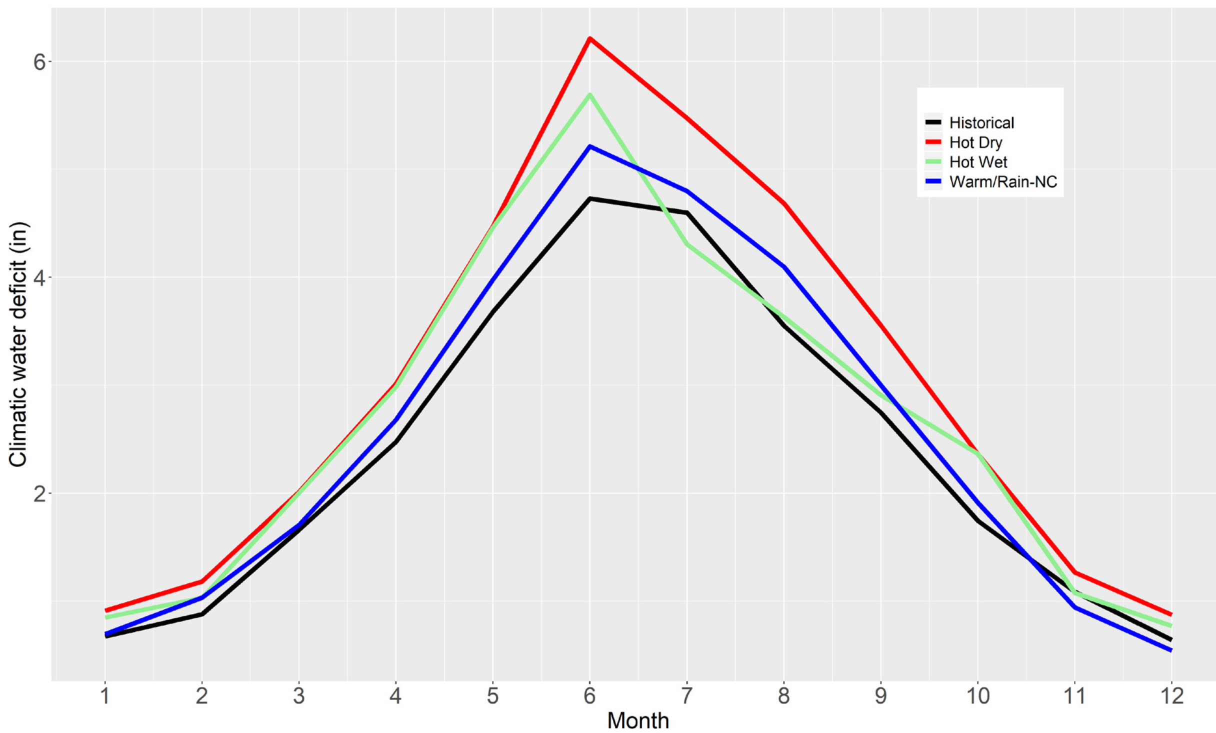

Figure B.2. Mean monthly climatic water deficit for WHSA based on historical conditions and for the three climate futures developed for WHSA. Water-balance model courtesy of David Thoma (NPS).

Figure B.3 shows a comparison of soil moisture between the historical reference period and the climate futures. Soil moisture is calculated as the soil remaining in the top 3 ft of soil that is not lost to evapotranspiration, runoff, or infiltration. All climate futures show a decline in soil moisture from historical conditions.

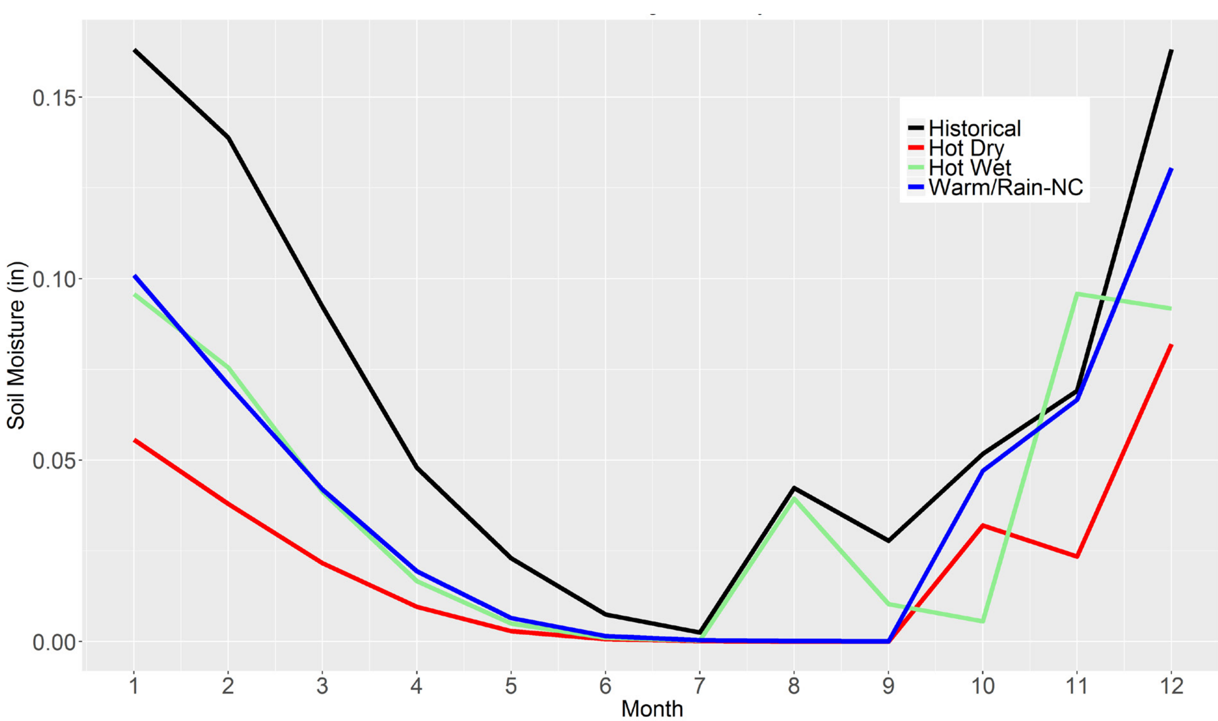

Figure B.3. Mean monthly soil moisture for WHSA based on historical conditions and for selected climate futures. Water balance model courtesy of David Thoma (NPS).

Appendix C. Expert Worksheets for Target Resources Based on Scenarios

Hypothesized Ecosystem Component (Resource) Response Worksheet

Your name: ___________________________________

Instructions: This worksheet records your thoughts about how the ecosystem component (resource) you study/know most about may respond to projected climate changes. Write in the name of the ecosystem component in the top left empty cell of the table below, and then for each row (scenario), fill in the four empty cells to describe 1) how you think the component will ultimately respond to this scenario, based on your understanding of the component's climate sensitivity (and adaptive capacity, where applicable), 2) how climate change leads to this response (i.e., describe the mechanism), 3) how certain you are of your hypothesis (High/Med/Low), and 4) sources of uncertainty (i.e., what would you need to know more about to be more sure of your hypothesis?)

Scenario	Ecosystem component (resource)	Likely response to this scenario	Mechanism behind response	Certainty (High/Med/ Low)	Source(s) of uncertainty
Warm/Rain-No Δ					
Hot Wet	(Same)				
Hot Dry	(Same)				

Research Next Steps (& Needs) to Better Understand Vulnerability Worksheet

Your name: ________________________________

Instructions: This worksheet captures your thoughts regarding how you might work to better understand how the ecosystem component (resource) that you study might respond to climate change. Please provide a detailed answer, and refer to the Hypothesized Ecosystem Component (Resource) Response worksheet that you filled out for the last exercise – and in particular your entry in the worksheet's "Sources of Uncertainty" column – to help you think about this.

Your study resource/component: _________________________

What can you do to better understand the climate change vulnerability of the element of the system that you focus on?	Who (i.e., what type of specialist) would you collaborate with to do so?	How could White Sands NM facilitate this research?	Additional notes/comments

Appendix D. Expert Opinions on the Hypothesized Resource Response to Projected Changes in Climate for White Sands National Park

Table D-1. Hypothesized resource response to projected changes in climate for White Sands National Park.

Scenario	Ecosystem Component (Resource or Process)	Likely Ecosystem Component Response to Scenario	Mechanism Behind Response	Certainty (High/Med/Low)	Source(s) of Uncertainty	Contributors	Notes
Warm/Precipitation-No Δ	Geomorphic and Hydrological Systems	Unkn/no change – balancing system as is; Δ in new crystal and sand production depends on timescale you're looking at.	–	–	Precipitation Events (frequency and magnitude of precipitation events).	–	Dune field has undergone major reorganization and actually accretion and addition of new dunes 3x in last 7,000 years; each of those events is associated with a major deflation event in the playas and on the alkali flats that's associated with a mega-drought that lowered the water table in places where it is normally most steady. As long as the water table can keep up, the stability of the dunes will remain.
Hot Wet	Geomorphic and Hydrological Systems	Unkn	–	–	–	–	More precipitation might just mean more sand
Hot Dry	Geomorphic and Hydrological Systems	Increase both dust and sand movement due to greater desiccation of the surface all the way across the park; increase in dune size and # (big sand supply and lots of potential availability, so lowering of water table	–	–	–	–	This scenario would result in the lowering of water table
Warm/Precipitation-No Δ	Dust Emission (productions) (i.e., getting the dust in the air, and how much)	Likely response at least as start is increase of dust emission/flux with warmer temperatures, at least to some extent.	We know that there is an inverse relationship between dust and land cover and dust and soil moisture – drier and more barren = more dust	Low/Med	Depends on steady supply of new sediments – assumes that new particles breaking down from larger ones to make dust. Certainty low/med b/c need to know more about internal dynamics of the hydro cycle w/in the basin – how close to surface for how long will water table be? Hydrology and water table on the one hand can keep interdune areas moistened and vegetated, but can also lead to salty groundwater evaporating and forming salty minerals.	Tom and Pat	Didn't even consider how soil crusts (which we know modulate dust) – if and when removed – will have major impact on dust. For this scenario, changes in hydro cycle will lead to lower soil moisture so there will be accumulation of dust – but it is a balance.
Hot Wet	Dust Emission (productions)	Decrease in dust emission b/c more plant cover and algae and fungi in soil and more crusted surfaces	–	Low/Med	–	Tom and Pat	Pat – same balance as stated above, but likely less accumulation b/c you will have more rain. More rain flushes out more; but again uncertainty b/c hydro cycle change.
Hot Dry	Dust Emission (productions)	Response likely the same as warm/rain – No Δ, but likely to have more dramatic seasonal variation	Higher amount of gypsum accumulation downwind – lower soil moisture and higher emission of dust and less rain to flush it out.	Low/Med	See comments above, but if you had hot/dry, would you decrease avail of dust particles. But Pat says you can't assume wind will stay constant. There's both availability of dust and avail of wind. Wind IS the big source of uncertainty. Hadley cell expansion northward is an important thing – even now, WHSA is proportionally dustier than rest of Chihuahuan Desert b/c just far enough north to get westerly dust storms; on days when not windy enough to make dust in El Paso. So if the tropics keep moving north, this region may actually become calmer, b/c dust storms and conditions that cause them move farther to the north. Some colleagues think things really will become calmer here. So, to recap, winds and hydro dynamics are the big uncertainties, along with nature and timing of extreme events.	Tom and Pat	Pat – focuses strongly on deposition of dust
Warm/Precipitation-No Δ	Playa Sand Source	Medium sand production	–	Low	Need more knowledge/lack of info	Patrick	–
Hot Wet	Playa Sand Source	Large sand production	–	Med	Lack of info	Patrick	–
Hot Dry	Playa Sand Source	No sand production, with potential for sand loss in terms of wind blowing it away	–	Med	Lack of info	Patrick	–

Table D-1 (continued). Hypothesized resource response to projected changes in climate for White Sands National Park.

Scenario	Ecosystem Component (Resource or Process)	Likely Ecosystem Component Response to Scenario	Mechanism Behind Response	Certainty (High/Med/Low)	Source(s) of Uncertainty	Contributors	Notes
Warm/Precipitation-No ∆	Biocrust-Coarse Resolution	Community shift – decrease in bryophytes (most sensitive to moisture); lichens can deal with drier, but we don't know re: temperature effects	Biology particularly sensitive to moisture	Low	No inventory data available; we don't know requirements of the spp that are there	Nicole	–
Hot Wet	Biocrust-Coarse Resolution	Community shift – especially bryophytes and lichens decreasing	Physiology – they will also face carbon deficit (hot and humid) – exposure to more pathogens	Low	No inventory data available; we don't know requirements of the spp that are there	Nicole	–
Hot Dry	Biocrust-Coarse Resolution	Community shift – bryos and lichens go down; algae community will shift (some can deal with hot/dry more than others) to a point where not enough moisture to sustain microbial life – in which case can lose majority of the community	–	Low	No inventory data available; we don't know requirements of the spp that are there	Nicole	There are other mechanisms behind response – e.g., geomorphic activity – more sand blasting means more negative impact. Herbivory is another potential mechanism. Shifts in community composition can also change albedo; shifts could be toward spp that aren't as good at binding particles.
Warm/Precipitation-No ∆	Gypsum-Endemic Plants	Minimal change likely in sp composition	If you look across n-s gradient of gypsum, they have similar communities, but species change	Low to Med	Depends on if scenario would have a lot of changes in dune dynamics and also if change happens quickly, it may overwhelm dispersal capabilities	Ben	–
Hot Wet	Gypsum-Endemic Plants	Veg communities likely lost or suffer significant change	–	High	Depends on how rainfall events (flooding) in interdunal areas – lots of endemics won't be able to take those wet conditions. sources of uncertainty – speed of change, dispersal, and colonization capacities	Ben	–
Hot Dry	Gypsum-Endemic Plants	Veg communities likely lost or suffer significant change	–	High	Lots of endemics won't be able to deal with speed of change, dispersal, and colonization capacities	Ben	–
Warm/Precipitation-No ∆	Endothermic Vertebrates	No change except possible extirpation for some species	Depends on whether or not organisms exceed physiological limits (but a bit warmer might be w/in limits)	Med	Don't have good info on plasticity and physiological tolerances	–	–
Hot Wet	Endothermic Vertebrates	Some species can't disperse; so potential extirpation. Others could disperse (so species leave) – so some community change	Physiological inability to thermos-regulate (limits exceeded)	Low	Don't have good info on plasticity and physiological tolerances	–	–
Hot Dry	Endothermic Vertebrates	Some species can't disperse; so potential extirpation. Others could disperse (so species leave) – so some community change	Physiological inability to thermos-regulate (limits exceeded); if humidity is low, species should be better able to thermos-regulate via evaporation if they have enough water to do so	Low	Don't have good info on plasticity and physiological tolerances, but where do species get their water – generally metabolic sources. Oryx will dig for water; what about other species?	–	–
Warm/Precipitation-No ∆	Arthropods (huge group)	Chance for slight decrease, but little change overall	–	Med	Difficult w/ inverts; different spp respond in different ways	Dave	Those arthropods assoc'd w/ veg will be more affected than subterranean – many species living in sand won't be much affected; above-ground spp that feed on live plants will respond in diff ways

Table D-1 (continued). Hypothesized resource response to projected changes in climate for White Sands National Park.

Scenario	Ecosystem Component (Resource or Process)	Likely Ecosystem Component Response to Scenario	Mechanism Behind Response	Certainty (High/Med/Low)	Source(s) of Uncertainty	Contributors	Notes
Hot Wet	Arthropods (huge group)	More plant production; arthropod diversity goes up	Increased plants = more resources for arthropods	Low	Need to understand how plants will respond; need to understand each species' life history and physiology; really need to break down to guilds, rather than a group this diverse/bit b/c we know so little	Dave	Use Cuatro Cienegas as a reference (warmer; wetter; higher plant and arthropod diversity)
Hot Dry	Arthropods (huge group)	Arthropod diversity goes down	Reduction in plant diversity/ productivity = decrease in arthropods	Low	Need to understand how plants will respond; need to understand each species' life history and physiology	Dave	Mechanism behind extreme events is important; an extreme event can extirpate a species
Warm/Precipitation-No ∆	Nematodes	Mild decrease in overall size of the population and high likelihood of shift in trophic ratios among species/groups	Increase temp will reduce length of time with sufficient soil moisture in macro-pores	Med	Don't know how warmer temps will affect cooler season – could make unavailable moisture (due to thermal requirement of 5–10C for them to be metabolically active) now available; don't know how tropics would shift b/c depends on fungal etc. influences and also macro/micro faunal effects	Steve	Soil nematode community is 100% dependent on sufficient soil moisture film in macro-pores to keep them active; otherwise they dry out and are inactive; four components determine community – herbivores, bacteria, fungi, and algae
Hot Wet	Nematodes	Increase in overall population and a change in trophic ratios	More moisture avail will increase period of activity	High – water = driver	We know nothing re: how food sources will be affected, but will drive the ratio	Steve	Soil nematode community is 100% dependent on sufficient soil moisture film in macro-pores to keep them active; otherwise they dry out and are inactive; four components determine community – herbivores, bacteria, fungi, and algae
Hot Dry	Nematodes	Substantial decline in overall community and trophic shift	No moisture = no nematode activity	High	We know nothing re: how food sources will be affected, but will drive the ratio	Steve	Soil nematode community is 100% dependent on sufficient soil moisture film in macro-pores to keep them active; otherwise they dry out and are inactive; four components determine community – herbivores, bacteria, fungi, and algae
Warm/Precipitation-No ∆	Lepidoptera	More lep diversity	More veg so more lep diversity	Med	–	Eric	Every plant species supports 7–8 leps; most leps are not generalists; dry and wet years are very different for moths
Hot Wet	Lepidoptera	More lep diverstiy	More (but different) veg – so more moths and a species shift	Med	Unknown – never experienced this scenario	Eric	–
Hot Dry	Lepidoptera	Fewer species and lower abundances, and also a shift in spp	Less veg variety and most taxa are host-specific	Low	Now experience with conditions like this scenario?	Eric	–
Warm/Precipitation-No ∆	Desert Bighorn Sheep	No drastic change, but potentially changed movements across the range	Lower soil moisture and increased temps lead to more movement across range	Low/Med	Limited knowledge of bighorns	John	–
Hot Wet	Desert Bighorn Sheep	No drastic change	More rain during monsoon won't lead to a change; won't have to search for water	Low/Med	Limited knowledge of bighorns	John	–
Hot Dry	Desert Bighorn Sheep	No drastic change, but could influence movement to new areas	Decrease in annual precip and soil moisture could reduce food availability and increased fire frequency could lead them to escape terrain	Low/Med	Limited knowledge of bighorns	John	–

Appendix E. Workshop Participant-Identified Research Needed to Better Understand Climate Driven Vulnerabilities for Resources at White Sands National Park

Table E-1. Workshop participant responses on types of research needed to better understand climate change driven vulnerabilities of resources at WHSA.

Name	Advisor's Resource or Component	What can you do to better understand climate change driven vulnerability of your resource component?	Who (i.e., what type of specialists) would you collaborate with?	How could WHSA facilitate this research?	Notes/Comments
Gary Roemer	Endothermic Vertebrates	Provide greater understanding of (1) natural history, (2) population dynamics, (3) sensitivity of vital rates, and (4) relationship between plant demography and physiology with regard to animal demography and plant physiology.	Physiological Ecologist, Plant Ecologist, Soil Scientist	Provide funding and/or alert researchers to potential funding opportunities; create and disseminate list of researchers working at park (including those that have deep knowledge of the systems at WHSA	–
Steve Thomas	Soil Nematode Community	Characterize and quantify nematode communities associated with different plant species and soil crusts. This would increase our ability to predict how nutrient reallocation will be affected in response to changing nematode ratios and prevalence.	Nichole Pietrasiak (Microbial Biocrust Specialist), Ben Cooper (Gypsum-Endemic Plant Specialist), and others	WHSA can continue to provide access and assist in identifying sources of funding to support sample collection and processing.	–
Tom Gill	Dust Emission	Define what controls formation of dust particles on or in White Sands	Hydrologist and Geochemist	Assist with permits for field work and monitoring and funding assistance	Please keep this conversation going!
Michael DeAntonio	Professor of Physics	Increase interaction and discussion between all researchers	–	Continue to provide collaborative meetings	–

Table E-1 (continued). Workshop participant responses on types of research needed to better understand climate change driven vulnerabilities of resources at WHSA.

Name	Advisor's Resource or Component	What can you do to better understand climate change driven vulnerability of your resource component?	Who (i.e., what type of specialists) would you collaborate with?	How could WHSA facilitate this research?	Notes/Comments
Ben Cooper	Gypsum-Endemic Plants	(1) Genetic/genome systematics of endemic gypsum plants to better understand populations genetic, species boundaries, evolution, and taxonomy and (2) develop common garden experiments to understand biology/ecology/ plasticity of gypsum endemic plants.	Botanists/Evolutionary Biologists	Continue access to research permits, assist in identifying sources for funding, change NPS voucher rules	–
Nicole Pietrasiak	Microbial Biocrust Specialist	Perform baseline inventory of organisms, perform niche modeling to figure out habitat requirements, and establish long-term monitoring to document changes over time.	Kerry Kundsen (UCR) lichenologist; Kristen R. (Jornada); and Theresa Clark (UNLR) Bryologists; Eric Metzer, Steve Thomas, Paul Delay and Liz? For Food Web Assessments; Tom Gill, Ryan, and Rick for Geomorphology >sediment movement, dust movement; and Cheryl Mcintyre Biocrust Inventory	Park can assist by providing logistical support, student support; funding opportunities for supplies, gas, and sequencing	–
Rip Langford	Geologist	Help identify what generated gypsum sand and dust; location of buried soils/crusts in parabolic area; and mapping of Alkali Flat.	Ewing, Kocaret, Gill, Knapp	Park can assist by providing a statement of utility	This work will add to our understanding of stability of soils and crusts and provide basic input data on sources of soil.

Table E-1 (continued). Workshop participant responses on types of research needed to better understand climate change driven vulnerabilities of resources at WHSA.

Name	Advisor's Resource or Component	What can you do to better understand climate change driven vulnerability of your resource component?	Who (i.e., what type of specialists) would you collaborate with?	How could WHSA facilitate this research?	Notes/Comments
Dave Lightfoot	Arthropods	Understanding how abiotic environment and vegetation will respond to climate change – this will provide for more informed scenarios; Learn more about the ecologies of more arthropod species at WHSA	Soil Scientists, hydrologists, plant ecologists, arthropod ecologists	Park can assist by developing and distributing lists of participating experts/researchers and assist with project funding.	This workshop has been very interesting and a useful process. I would like to remain involved.

Appendix F. Accessible Table 2

This appendix contains a copy of Table 2 that has been augmented here to be more accessible by people that depend on special screen readers for the visually and cognitively impaired, color-blind, etc. Additionally, there is a hyperlink in the table caption that will take the user back to the original table in the narrative.

Table F-1. Hypothesized resource responses to climate futures for White Sands National Park. This is a more accessible version of Table 2 in the narrative that is designed specifically to be easier to read by screen reading software for people with certain visual and cognitive impairments; or with low vision, various types of color-blindness, or cannot read the text against some of the table cell background colors used.

Ecosystem Component	**Warm and No Precipitation Change**	**Hot and Wet**	**Hot and Dry**
Geomorphic & Hydrological Systems	No change or minimal change from current condition; low certainty	Uncertain or unknown response	Negative response; medium certainty
Dust Emissions	Negative response; medium certainty	Positive response; medium certainty	Negative response; medium certainty
Playa Sand Source	Positive response; low certainty	Positive response; medium certainty	Negative response; medium certainty
Biocrust – Coarse Resolution	Negative response; low certainty	Negative response; low certainty	Negative response; low certainty
Gypsum-Endemic Plants	No change or minimal change from current condition; low certainty	Negative response; high certainty	Negative response; high certainty
Endothermic Vertebrates	No change or minimal change from current condition; medium certainty	Negative response; low certainty	Negative response; low certainty
Desert Bighorn Sheep	No change or minimal change from current condition; medium certainty	No change or minimal change from current condition; medium certainty	Negative response; low certainty
Lepidoptera *spp.*	Positive response; medium certainty	Positive response; medium certainty	Negative response; low certainty
Arthropods	No change or minimal change from current condition; medium certainty	Positive response; low certainty	Negative response; low certainty
Nematodes	Negative response; medium certainty	Positive response; high certainty	Negative response; high certainty

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