



Dune Stability and Integrity Monitoring Protocol for the Gypsum Dunefield in White Sands National Monument

Version 1.00

Natural Resource Report NPS/CHDN/NRR—2018/1842



ON THE COVER

Dunefield, White Sands National Monument, New Mexico. NPS photo.

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Natural Resource Report NPS/CHDN/NRR—2018/1842

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Acronyms and Abbreviations

AFB:	air force base
ASTER:	Advanced Spaceborne Thermal Emission and Reflection
CHDN:	Chihuahuan Desert Network
cm:	centimeters
DAAC:	Distributed Active Archive Center
DEM:	digital elevation model
ETM:	Enhanced Thematic Mapper
EVI:	enhanced vegetation index
GIS:	geographic information system
GPS:	global positioning system
I&M:	inventory & monitoring
IMR:	Intermountain Region
km:	kilometers
LiDAR:	Light Detection and Ranging
m:	meters
μm:	micrometer
MODIS:	Moderate-Resolution Imaging Spectroradiometer
MR:	missile range
NAIP:	National Agricultural Imagery Program
NASA:	National Aeronautics and Space Administration
NDVI:	Normalized Difference Vegetation Index
NDWI:	Normalized Difference Water Index
NM:	national monument
NPS:	National Park Service
NRR:	Natural Resource Report
OLI:	Operational Land Imager
ppm:	parts per million
SOP:	standard operating procedure
TM:	Thematic Mapper
VNIR:	Visible and Near Infrared Radiometer

Abstract

This protocol outlines the justification, objectives, and procedures for long-term monitoring of vital signs critical to ensuring the long-term stability and integrity of the White Sands dunefield at White Sands National Monument (NM), New Mexico. This protocol supplements a separate effort by Smith and others (2016), which uses LiDAR in a subset of the dunefield to assess geomorphological processes related to individual dune movements, sand transport dynamics, and morphological changes in dunes as they migrate across the dunefield.

This protocol will assess the persistence, fate of, and changes to the entire dunefield by monitoring physical, locational, and vegetative changes that provide insight into dunefield stability and integrity. Together, these protocols will help identify conditions of concern for park managers at White Sands National Monument, the National Park Service, and the public at large.

This protocol describes and assesses how serial remote-sensing images (from historical to future) can be used to detect and evaluate specific, large-scale changes to the size, location, and integrity of the dunefield at White Sands NM. It also describes a framework for imagery and image-analysis approaches that can help us to evaluate stability (e.g., movement, migrations, changes in size) and integrity of the entire dunefield through the maintenance drivers of dune movement, morphology, and function. Serial remotely sensed images can be used to obtain quantitative insights into whether the dunefield size, shape and/or location is changing over time and what those changes might represent (e.g., if the dunefield is expanding, declining, or oscillating in size, and if so, why). Monitoring these metrics will provide insight into the dynamics of the dunefield, whether it is changing in one direction (i.e., establishing a trend of concern) rather than oscillating, and into the ecophysiographic mechanisms that help maintain the current dunefield. Remote-sensing imagery can also be used to evaluate whether the integrity of the dunefield is intact, as indexed by changes in vegetation which, in turn, indexes other possible changes to the ecosystem.

These metrics can be adapted for analysis of changes in other dunefields—in particular, gypsum dunefields that occur in Guadalupe Mountains National Park, Texas, and Quatrociene-gas, Coahuila, Mexico. These metrics are also of concern to the adjacent Holloman Air Force Base and White Sands Missile Range. Destabilization of the White Sands dunefield would affect the operations of both facilities.

This protocol contains (1) the background and rationale for monitoring the gypsum sand dunes in White Sands National Monument, NM, (2) program goals and objectives, (3) research sampling design, (4) analytical methods, (5) data management, (6) analysis and reporting, (7) personnel requirements and training, (8) operational requirements, and (9) procedures for revising and reviewing the protocol. Standard operating procedures that describe the implementation of all aspects of this protocol are provided in supplemental documents.

Acknowledgements

We thank Marie Sauter, superintendent at White Sands National Monument (NM), for facilitating the logistics on these studies, and the staffs at White Sands NM and the Chihuahuan Desert Network for their dedication to excellence in serving White Sands NM on behalf of Americans who treasure their national parks. Special thanks to Marcia Wilson, Cheryl McIntyre, Mark Isley, Julie Christian, Tim Pine, and Megan Podolinsky, who engage in long-term monitoring of the resources of White Sands NM.

Protocol Narrative

Revision History Log

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1 Introduction and Background

This sampling protocol consists of this protocol narrative and the following standard operating procedures (SOPs), available at <https://irma.nps.gov/DataStore/Reference/Profile/2258531>:

- SOP 1: Operations and Timeline
- SOP 2: Georeference and Evaluation Check
- SOP 3: Creating Difference Maps
- SOP 4: Vegetation Greenness NDVI/EVI using MODIS
- SOP 5: Estimating Soil Moisture
- SOP 6: Reviewing This Program and Processes
- SOP 7: Revising the Protocol Narrative and SOPs

1.1 General

White Sands National Monument (NM) was established in 1933 to “protect the White Sands Dunefield and associated items of scientific and educational interest.” This dunefield, and the ephemeral saline lake system that supplies it with gypsum, are located within White Sands NM and the adjacent Holloman Air Force Base (AFB) and White Sands Missile Range (MR) (Figures 1 and 2). This protocol uses remote sensing to provide the best objective, repeatable, and cost-effective means to monitor landscape-level change in dunefield condition (e.g., persistence, size, location, and integrity) by tracking trends of key metrics important to the maintenance of this unique resource.

Unique geological processes at White Sands NM and adjacent lands in the Tularosa Basin

have created the largest gypsum dunefield in the world. Visitors are visually drawn to the stark contrasts of the desert environment and the juxtaposition of soft, flowing white sands against the darker rock background. Perhaps less well-appreciated are the biophysical processes that sustain the active dunefield and its ecosystem, which supports habitats for endemic plants and animals. Here, a suite of insects, arachnids, reptiles, amphibians, and mammals indigenous to the White Sands dunefield exhibits lighter colors than close

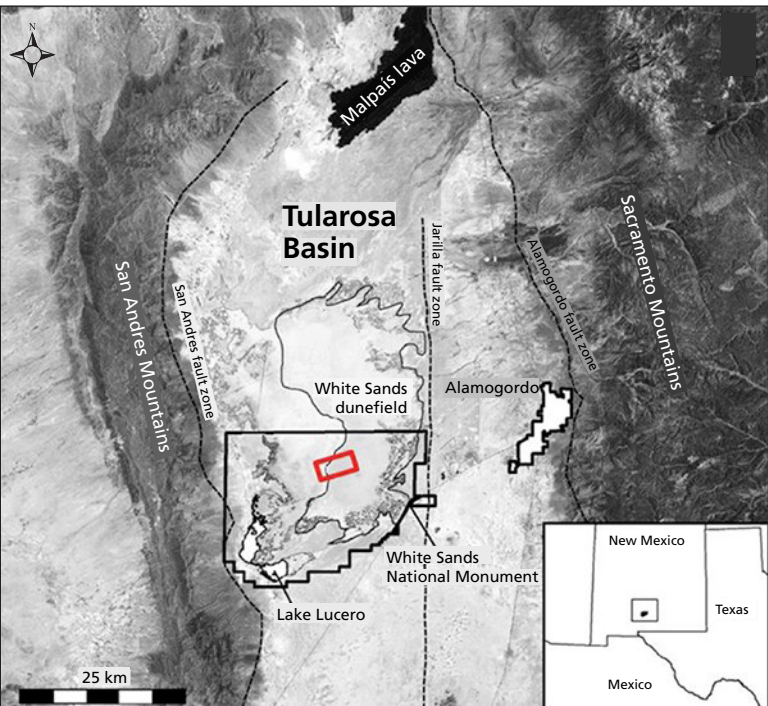


Figure 1. Location of the White Sands dunefield within the Tularosa Basin. Note the delineation of two faults on either side of the dunefield and Lake Lucero, the source of wind-blown gypsum sand that makes up the dunefield. The red rectangle indicates the location of the LiDAR field being monitored in the Dune Dynamics Protocol for White Sands National Monument (Kocurek et al. 2012).

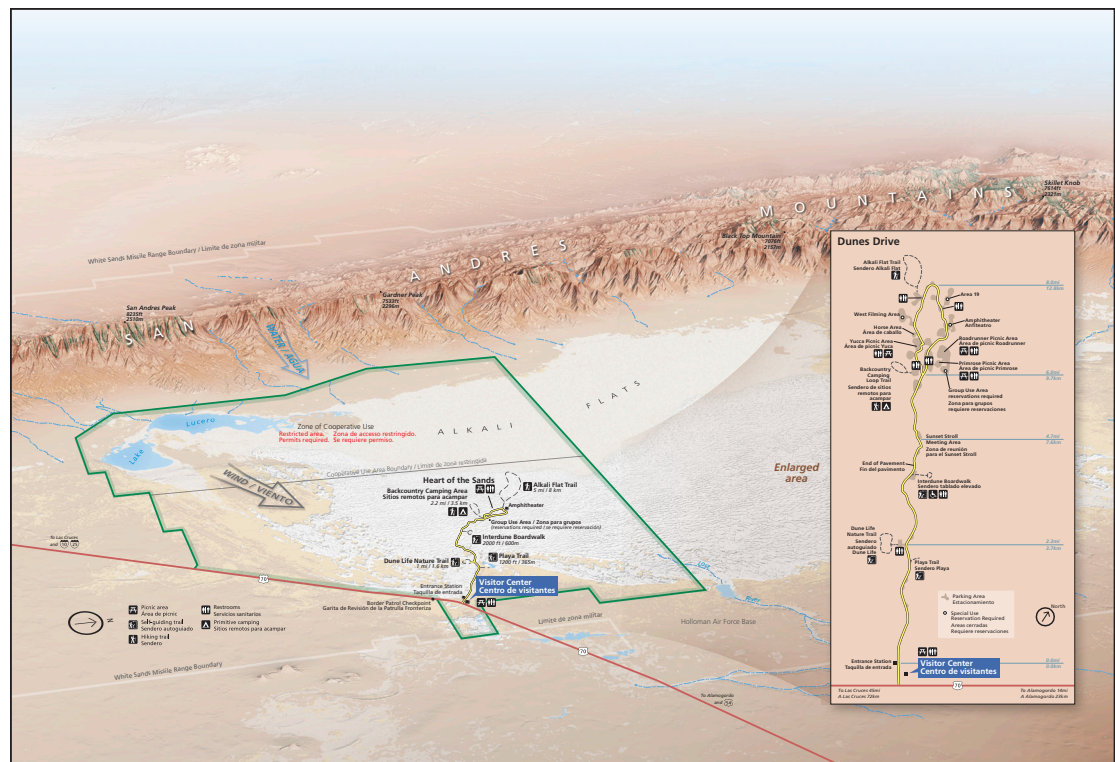


Figure 2. Property boundaries for the White Sands dunefield within White Sands National Monument (showing park boundaries) and bounded by Holloman Air Force Base and White Sands Missile Range.

relatives, as well as other adaptations (Benson 1933, Bugbee 1943, Dixon 1967, Lowe and Norris 1956, Stroud 1950, Rosenblum 2006, Des Roche et al. 2015).

Two prominent resource management concerns affecting the White Sands dunefield are its physical long-term stability (i.e., persistence, size, and location) and the physical and biotic integrity of the dunefield system (i.e., the processes creating and affected by the dunefield and the biotic community it supports). Stability assessments can ascertain whether the White Sands dunefield is changing in size (e.g., increasing or decreasing), and/or if it is moving or migrating from its current and/or historical location. Integrity assessments measure aspects of the dunefield that reflect interacting physical and ecological dynamics, primarily affecting native vegetation that has adapted to the dunefield's unique climatic, edaphic, hydrologic, and morphologic characteristics. Changes in vegetation land coverage (i.e., area, density) can be a direct measure of fundamental ecosystem changes. In turn, vegetation communities affect which organisms can successfully use the dunefield for food and cover.

These two facets of dunefield dynamics (stability and integrity) complement each other synergistically and can co-reveal changing conditions of concern to resource staff at White Sands National Monument, the National Park Service (NPS), and the public at large. Monitoring these two metrics will allow the Chihuahuan Desert Network (CHDN) to assess changes to critical hydrologic components, such as soil moisture, which are necessary for dune stability. Vegetation changes also reflect soil moisture availability, as plants are specifically adapted to the hydrologic conditions of their environment (e.g., climate, soil moisture, and groundwater).

Because climate, hydrology, and wind effects interact at broad spatial scales, analysis of historic and current conditions within the monument boundary—and beyond it—is imperative to protect the health of the White Sands dunefield. This protocol is designed to complement and supplement two other monitoring protocols: (1) a five-year, recurring, LiDAR-based survey of dune dynamics within the dunefield by Smith and others (2016), Kocurek and others (2012), and (2) a

five-year, recurring, vegetation survey conducted by the Chihuahuan Desert Network (Hubbard et al. 2012).

This protocol was developed to provide park managers with timely, quantitative information on the overall dune system using inexpensive remote-sensing technology. Remote sensing provides a cost-effective, practical means of evaluating the overall long-term stability and integrity of the dunefield at a landscape scale. This protocol will provide the opportunity for scientific decisionmaking within White Sands National Monument and the surrounding communities when combined with the LiDAR and vegetation monitoring protocols and rigorous field research by park personnel and collaborators.

1.2 Legislative Framework for Dune Monitoring

The National Park Service Organic Act of 1916 (P.L. 64-235, 39 Stat. 535) established the National Park Service and directed it to “conserve the scenery and the natural and historic objects and the wild life therein and to provide for the enjoyment of the same in such a manner and by such means as will leave them unimpaired for the enjoyment of future generations.” President Herbert Hoover established White Sands National Monument through Proclamation No. 2025 on January 18, 1933 (47 Stat. 2551) for “the preservation of the white sands and additional features of scenic, scientific, and educational interest” and placed them under the management and control of the NPS. Congress reaffirmed this relationship with the General Authorities Act of 1970 (16 USC 1a–1a8) that created a “National Park System” unified in management toward the common purposes of preservation and study.

The National Parks Omnibus Management Act of 1998 (Public Law 105-391) directed the Secretary of the Interior to “. . . to establish baseline information and to provide information on the long-term trends in the condition of National Park System resources.” NPS management created the Inventory and Monitoring Division and its 32 networks (including the Chihuahuan Desert Network) to inventory and monitor natural systems

within parks with significant natural resources (NPS 2001).

To describe long-term trends in landscape properties, CHDN monitors “vital signs” in NPS units of the Chihuahuan Desert. Vital signs, as defined by the NPS, are a subset of physical, chemical, and biological elements and processes of park ecosystems that are selected to represent the overall health or condition of park resources (CHDN 2010). In 2010, the Chihuahuan Desert Network Vital Signs Monitoring Plan called for the development of protocols for monitoring the core vital signs of (1) dune formation and stability, and (2) dune morphology (CHDN 2010). Understanding these processes and their ongoing changes will provide the science needed to manage them in perpetuity.

As a result, the *Dune Dynamics Monitoring Protocol for Gypsum Dunefields in White Sands National Monument* (Smith et al. 2016) was developed. That protocol uses LiDAR technology to accurately monitor dune morphology as it changes over time. However, this effort did not address the stability and integrity of the overall dunefield, which are important management concerns. To preserve the dunefield and establish appropriate management practices to achieve that goal, park managers need to receive information on changes to the overall size, location, and integrity of the dunefield on a regular basis.

1.3 Rationale for Dune Monitoring

There are numerous reasons to monitor the dunefield. The gypsum sands and geologic setting that create the peculiar environment at White Sands NM are a unique, world-class resource. They comprise the largest gypsum dunefield on Earth and are an excellent analog for other, smaller, gypsum dunefields worldwide—many of which have been degraded by human activities, including direct mining and groundwater pumping. The destruction or degradation of other gypsum dunefields has shown that gypsum dunefields are incredibly sensitive to perturbation. This makes the White Sands dunefield even more important. Its protected status allows researchers to understand not only the resource, but also the processes that need pro-

tection to sustain it. In addition, the suite of unique habitats created by the dunefield has yielded a distinct ecosystem that is home to a wide array of endemic species adapted to this environment. Moreover, the dunefield's location adjacent to two military installations makes it imperative that the dunes remain stable. If the dunes become destabilized, blowing and drifting sand may impact operations and equipment at neighboring Holloman AFB and White Sands MR.

1.3.1 Scientific Significance

Gypsum dunefields are rare on Earth. They can only form in arid environments, including marine coastal or inland lacustrine areas that have a surficial source of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) that is transported via eolian processes to the dunefield (Szynekiewicz et al. 2010). As one of these rare habitats, the White Sands dunefield results from complex interactions of local geology, tectonics, climate, and hydrology (Szynekiewicz et al. 2010).

The White Sands dune system is young and fragile, and remains the subject of fundamental research to understand its basic properties and ensure its protection and persistence. For instance, a shallow water table helps maintain high sediment moisture close to the dune surface through capillary wicking, a process critical to maintaining the dunes (Scheidt et al. 2010 and references therein). This moisture regime may change because of excessive groundwater pumping and/or other alterations of the hydrologic system due to surrounding land uses or climate change.

The White Sands dunefield is also considered a terrestrial analog for the formation of the sulfate-rich eolian deposits on parts of Mars (Szynekiewicz et al. 2010, KellerLynn 2012). Crystal pedestals and domes, along with cracks and fins, found in the White Sands dunefield have been studied in order to better understand Martian features.

1.3.2 Environmental Sensitivity

Monitoring potential environmental change, and the drivers of that change, is paramount to preserving the White Sands dunefield. There are two other gypsum dunefields in

the Chihuahuan Desert ecoregion: the Salt Basin dunefield (west of Guadalupe Mountains National Park) and the Cuatrocieneegas dunefield (Coahuila, Mexico). Both are in decline (i.e., reduced in size, volume, and area), and may portend a possible scenario for the White Sands dunefield. Given the changing land-use patterns within and adjacent to the Tularosa Basin, the White Sands dunefield could be in jeopardy.

The nearby but unrelated Salt Basin dunefield (10 km²) is believed to be declining as the processes that supply gypsum sand to the dunefield are reduced over time (Janet Coles, pers. comm.). Lake King, east of Guadalupe Mountains National Park, was the source of gypsum blown by westerly winds and deposited at the base of the Guadalupe Mountains. Lake King is a remnant of an ancient lakebed. It is now a dry salt basin, hydrated only occasionally for short periods. The Salt Basin dunefield is similar to the White Sands dunefield in terms of sediment-transport processes (e.g., wind direction, wind energy, sediment particle dynamics). However, lower groundwater levels and less-frequent rehydration in the Salt Basin have reduced the interactions between groundwater and sediment moisture that counterbalance wind energy and reduced surficial gypsum sources, thus causing a shift to silica-based dune deposition from sources west of the gypsum sands (Wilkins and Currey 1999, Tchakerian et al. 2002).

The Cuatrocieneegas was once the world's second-largest gypsum dunefield. It has been in decline due to anthropogenic disturbances, including (1) the direct quarrying of gypsum sand and (2) water diversion that has lowered the water table in some areas, contributing to wind erosion and evacuation. It is estimated that 80% of the original dunefield has been lost during the last century (Szynekiewicz et al. 2010).

Human activities on the landscape beyond White Sands National Monument, such as solar or wind farms or military activities, may influence the system. Desalination plants and other, large-scale groundwater withdrawal projects may also serve as destabilizing stressors.

1.3.3 High Degree of Endemism

The bright-white gypsum of the White Sands dunefield has created an “island” ecosystem in which strong selective pressures lead to a large degree of endemism. Ongoing research has identified more than 50 new and unique species living in White Sands NM (WHSA 2016) that have evolved rapidly since the formation of the dunes, roughly 7,000 years ago. This suite of insects, arachnids, reptiles, amphibians, and mammals, which exhibit lighter colors than their relatives (as well as other adaptations), represents unique taxa endemic to the White Sands dunefield (Benson 1933, Bugbee 1943, Dixon 1967, Lowe and Norris 1956, Stroud 1950, Rosenblum 2006, Des Roche et al. 2015). These endemic species underscore the sensitivity and importance of this resource.

1.3.4 Potential Impacts to Neighboring Military Installations

The destabilization of the dunes may cause more than just the loss of this unique national treasure. The downwind dune margin of the field, adjacent to Holloman AFB, has been relatively stable for decades. If the dynamics of the dune margin begin to change, the results could cause critical military assets at Holloman AFB and White Sands MR to become ineffectual (CHDN 2010). Holloman AFB has particular concerns about the stability of the dunefield. If the dunes become destabilized, blowing and drifting sand would likely impact their operations and equipment. This stability and integrity protocol, in conjunction with the dune dynamics protocol (Smith et al. 2016), will establish an “early warning” system for identifying changes in dune sedimentology and hydrology, and provide managers with quantitative scientific information for scientifically informed decisionmaking. This protocol may also foster additional collaboration between NPS and the Department of Defense.

1.4 Overview of White Sands Dunefield

1.4.1 Management Responsibility

The White Sands dunefield is entirely within White Sands NM, White Sands MR, and

Holloman AFB (see Figures 1, 2). Extending beyond the dunefield proper, but affecting the dunefield, the majority of the Tularosa Basin floor is controlled by the Department of Defense, National Aeronautics and Space Administration (NASA), Bureau of Land Management, and the NPS. While the basin is managed by a variety of entities, the overall management of the dunefield proper is the responsibility of the three agencies that have a portion of the dunefield on their properties. Of those, only White Sands NM is primarily dedicated to resource protection.

1.4.2 Geographic and Geologic Setting

Fryberger (2003) provides a comprehensive overview of the geology of the White Sands dunefield, which covers about 712 square kilometers of the Tularosa Basin (see Figures 1 and 2).

The Tularosa Basin, a southern extension of the Rio Grande Rift, is a tectonic feature consisting of a series of interlinked, asymmetric grabens stretching from Leadville, Colorado, to Mexico. Rifting initiated when subduction geometry changed as the Farallon Plate was completely subducted under North America, bringing the Pacific Plate directly into contact with the North American Plate. As a result of this tectonic activity, the Tularosa Basin formed in the Rio Grande Rift after marine deposits were uplifted into a dome and then later collapsed as Earth’s crust pulled apart (Langford 2003, Kocurek et al. 2007).

The basin is bounded by large, down-to-basement, normal faults that created up to six kilometers of relief and subsequently filled with basin sediment eroding from adjacent mountain ranges. The remnants of that dome are topographically visible as the San Andres Mountains, which bound the basin to the west, and the Sacramento Mountains, which bound it to the east. The basin is also bounded by the Sierra Blanca Mountains and the Carizozo volcanic field to the northeast. Moreover, the northern part of the basin had extensive lava flows within the last 10,000 years, when hundreds of square miles of basaltic lava were extruded onto the surface. Permian sedimentary rocks exposed in the San Andres and Sacramento mountains are also present in the subsurface below the basin itself.

The Tularosa Basin floor is dominated by an ephemeral lake (playa) system consisting largely of ephemeral saline lakes, saline mud flats, dry alluvial fans, ephemeral stream channels, and the White Sands gypsum dunefield. The basin is an internally drained (closed) system, with runoff from the surrounding mountains flowing into its lakes and mud flats. Lake Lucero is the largest remaining remnant of Pleistocene Lake Otero, which nearly filled the basin during wetter periods. Lake Lucero and the adjacent Alkali Flat lie just west and upwind of the dunefield (see Figures 1 and 2).

1.4.3 Sediment Source

The gypsum in the system was originally derived from the Permian sedimentary rocks that bound the Tularosa Basin. These sources contained gypsum and other evaporate minerals that were deposited in marine, restricted marine, and coastal sabka environments and are the primary source of gypsum for the Tularosa Basin playa and dune system (KellerLynn 2012). Gypsum is soluble, so as these mountains eroded, it was transported primarily in solution via surface and groundwater flows to the ephemeral lakes in the basin. Over time, gypsum accumulated on the lake bottoms and associated mud flats, and in groundwater. The below-surface portions of these gypsum-rich sedimentary layers also contributed to subsurface gypsum concentrations in groundwater. The episodic drying of these lakes, which exposes the gypsum to wind, provides the terrestrial source of the gypsum sand in the dunefield (Langford 2003).

Flooding events episodically bring solutes into the system through dilute runoff or groundwater brines (>5,000 ppm solutes). Evaporation concentrates the solutes in surface waters. Alkali earth carbonates and dolomite are precipitated from the water first. As evaporation continues, the water becomes super-saturated with calcium (Ca) and sulfate (SO_4), and gypsum will come out of solution as a chemical flocculation or through bottom-growth crystals. Today, much gypsum also moves into Lake Lucero as dissolved solids via groundwater percolation. It seeps through the Permian evaporates of the

ancestral Lake Otero Basin (the current location of Lake Lucero); then, during seasonal periods of circulation, it precipitates out (Szynkiewicz et al. 2010). Gypsum crystals may grow directly from the groundwater and displace crystals in the subsurface. Eventually, chemical differentiation may result in the presence of more-soluble salts, such as halite (NaCl), in the system, but it is unclear if this occurs in the Tularosa Basin. As Lake Lucero water levels recede after periods of wetter weather events, gypsum forms distinct crusts on soil surfaces as a product of precipitation. As water evaporates, hard gypsum cements sand grains together. Gypsum crusts may also form as secondary deposits of sediment re-worked by wind and water across the dunefield.

1.4.4 Evolution of the White Sands Dunefield

A time sequence developed by Szynkiewicz and others (2010) shows the development of conditions that led to the current White Sands dunefield (Figure 3). The following text summarizes this work. A combination of geological and limnological processes created the local source of gypsum, while current climatological factors lead to its erosion and transport. In particular, wind transports gypsum sand from its source on Alkali Flat and associated terraces and mudflats to the dunefield, where groundwater provides the ideal hydrologic and edaphic conditions to moisten and stabilize the sand, counteracting the wind energy. Thus, stability of the dunefield is believed to be influenced by the intersection of unique wind, precipitation, groundwater, interstitial moisture, and vegetation dynamics.

In the dunefield, “sand” is a scientific term used to describe sediment with a grain size between 62 and 2,000 μm . In this protocol, however, we refer all sediment in the dune system as “sand.” Sand within the system varies in size, ranging from gypsum “blades” (i.e., elongated crystals) the size of coarse gravel to fine silt and dust. Particle size follows a general longitudinal gradient across the dunefield from larger to smaller. Gypsum sand is softer than quartz sand. Thus, it breaks down more quickly into smaller par-

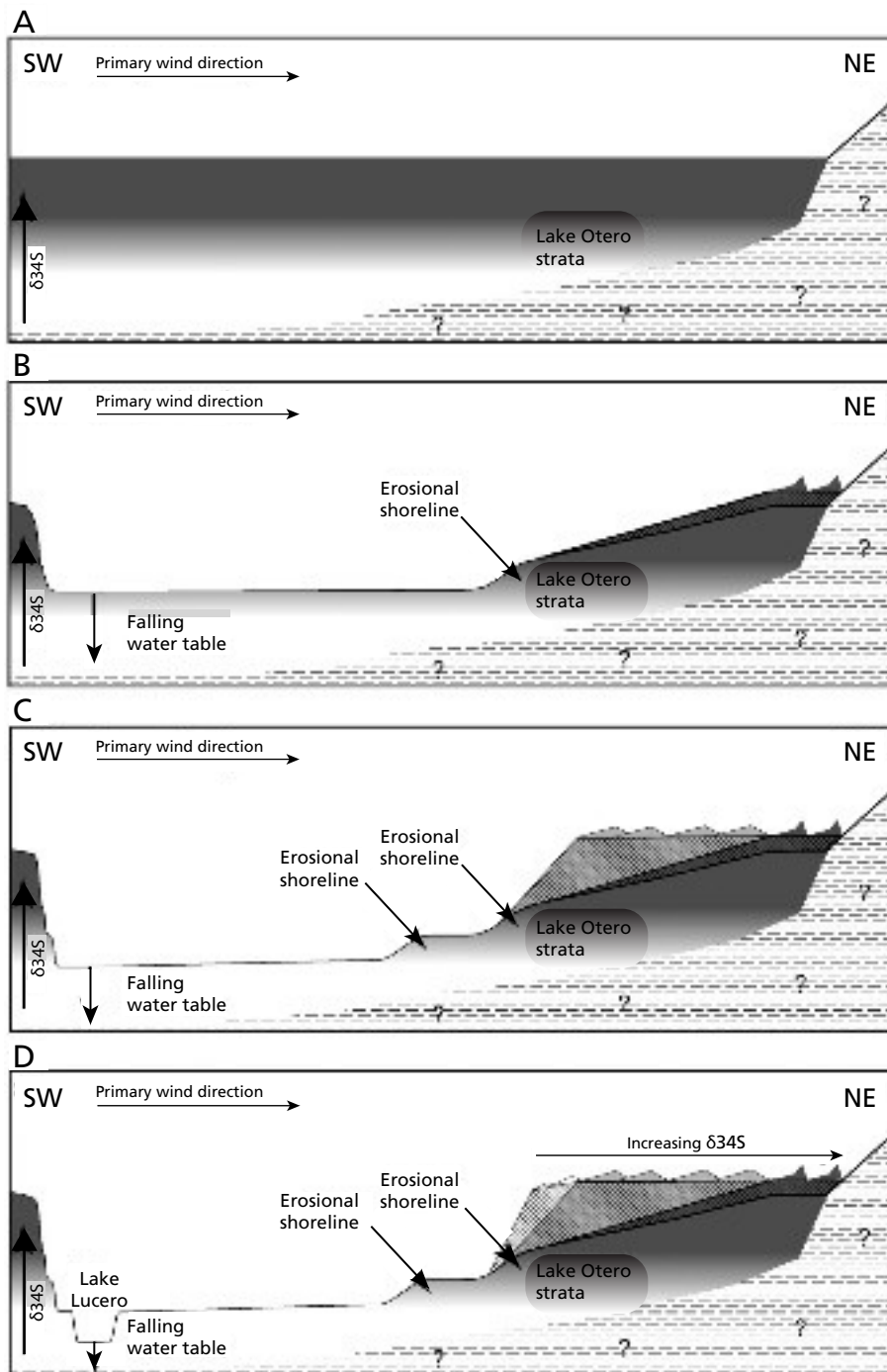


Figure 3. Simplified conceptual model showing the evolution of the White Sands dunefield as inferred from the spatial distribution of eolian gypsum sand and from previous work recognizing erosional shorelines within the basin (from Langford 2003, Kocurek et al. 2007). (A) Shows the state of the basin prior to the onset of the deflationary events in the mid-Holocene. The gradient shading indicates an upward increase in the measured $\delta^{34}\text{S}$ values in the Lake Otero strata. Note the prevailing wind direction from the southwest to the northeast. (B) Shows deflation to a lower water-table, which created an erosional shoreline. The deflated, high $\delta^{34}\text{S}$ -value, Lake Otero strata accumulated at the downwind extent of the current dunefield into what are today parabolic dunes. Note the dune accumulation is marked by the angular-line fill above the gradient fill of the Lake Otero strata. (C) Denotes another major deflationary event, corresponding to the primary accumulation of the dunefield postulated by Langford (2003). The dunes on top of the accumulation represent crescentic ridges that comprise the core of the dunefield. (D) Shows a final stage of deflation and the modern state of the basin, with playa Lake Lucero marking the lowest elevations. Modified from Szyrkiewicz and others (2010). Used with permission.

ticles, making wind transport easier. Within the White Sands dunefield, sand is initially deposited as crescentic and barchan dunes bordered by parabolic dunes of smaller grain size to the north, east, and south. Individual dunes migrate in the downwind direction at an average rate of about three meters per year and behave differently depending upon the season, transport direction, location within the dunefield, and position relative to other dunes (Ewing and Kocurek 2010). Understanding the changes in dune shape and size, and their rates of migration, is the focus of the dune dynamics protocol (Smith et al. 2016).

Individual dunes have microenvironmental gradients, with moisture varying along a longitudinal cross-section. Sand erodes from the face and is deposited on the lee side (Smith et al. 2016). As dunes migrate, the interdunal environments shift. Plants in the dunefield have adapted to these processes and changing conditions. In general, vegetation density increases downwind in the dunefield (Wasson and Hyde 1983, Lancaster and Baas 1998), where particle size and plant colonization create conditions causing crescentic dunes to transition to parabolic dunes. Plant colonization is thought to increase at a critical level of sand-surface stability that occurs due to a downwind reduction in the sand-transport rate (Scheidt et al. 2010). Enhanced plant colonization further reduces dune mobility, which in turn promotes more vegetation growth. Langford and others (2009) also believed that reduced salinity downfield contributed to increased plant colonization. Destabilizing events from any source could disrupt these general patterns, affecting the integrity of the entire system.

One of the most intriguing aspects of the White Sands dunefield is its abrupt, distinct, downwind terminus along the eastern edge (Pelletier and Jerolmack 2014). Despite prevailing winds from west to east, the dunefield stops at a clearly demarcated, conspicuous border along its east margin; there is no gentle transition of gypsum deposits or drifting beyond this demarcation to the east. Interestingly, this eastern boundary lies near the Jarilla Fault zone, which may be key to explaining this abrupt change. Groundwater

flow appears to be intercepted at this fault, with the water table dropping to the east. Because capillary action of groundwater (wicking moisture up into the dunefield) appears important to holding the dunes in place, it is likely interrupting the groundwater–gypsum sand-stabilizing dynamic found to the west. This demarcation makes the area east of the fault drier, with groundwater less able to anchor the migrating sand. Beyond that fault, sand blown from the dunefield is rarely deposited locally in any substantial amounts. Rather, it is transported east/northeast, to Texas and Oklahoma. Moreover, because gypsum is softer than quartz sand, it erodes more quickly as it is transported across the dunefield and these smaller particles found on the east side of the dunefield make their exit from the system more easily.

1.4.5 Flora and Fauna

1.4.5.1 Flora

Vegetation at White Sands NM is adapted to drought conditions and saline, alkaline, and nutrient-poor soils. Species of interest include grasses, such as alkali sacaton (*Sporobolus airoides*) and little bluestem (*Schizachyrium scoparium*), and Rio Grande cottonwood (*Populus deltoides wislizenii*).

Grasses and their seeds are important food sources for animals inhabiting the White Sands dunefield, where food availability is limited. Grasses at White Sands colonize interdunal areas, where the water table is closest to the surface. Alkali sacaton (*Sporobolus airoides*) can withstand partial burial and higher salinity. Little bluestem (*Schizachyrium scoparium*) is limited by water availability, as precipitation at White Sands barely meets its minimum physiological requirements.

Rio Grande cottonwood (*Populus deltoides wislizenii*) is the primary tree species occurring in White Sands NM. This tree is indicative of conditions where groundwater lies close to the surface. Recruitment of young cottonwoods, in particular, requires groundwater levels to be near the dunefield surface (Mahoney and Rood 1998).

Tamarisk (*Tamarix* sp.), an invasive exotic plant, greatly affects dune migration and

geomorphological dynamics—it can continue to thrive even when buried. As a result, non-typical sand pedestals form around tamarisk, disrupting the dunefield configuration and dune migration patterns.

1.4.5.2 Fauna

Animals at White Sands NM are not only diverse, but also have a high degree of endemism associated with color adaptations to the surrounding white gypsum sands. At least 220 species of birds, 27 species of herpetiles, 11 species of mammals, 600 species of invertebrates, and 1 species of fish have been reported from the park. A number of species/subspecies have adapted to the white sand over time, becoming lighter or white, including the Apache pocket mouse (*Perognathus flavescens Apachii*), the bleached earless lizard (*Holbrookia maculate ruthveni*), sand treader camel cricket (*Daihiniodes larvale*), and over 35 species of endemic white moths. On the other hand, some species of invertebrates that are less palatable to predators, such as the darkling beetle (*Fam: Tenebrionidae*) and harvester ants (*Pogonomyrmex maricopa*), have no such color adaptation.

1.4.6 Hydrology

1.4.6.1 Groundwater

Groundwater is key in regulating the dynamics of the dunefield, and is integral to its stability (Szynkiewicz et al. 2010). Figure 4 shows a generalized dune cross-section relative to groundwater. Shallow groundwater stabilizes the dunes via adhesion and cohesion. Capillary action wicks groundwater into the dunes (Brady and Weil 2002), with the height of capillary rise roughly a function of pore size between particles. This relationship can be estimated as

$$h = \frac{0.15}{r}$$

where h = capillary rise and r = pore radius, both expressed in centimeters. The simple form of this equation suggests the possibility of estimating depth to the capillary fringe, using the assumption that pore size is equivalent to the smallest particle size.

The dynamics of groundwater elevation and soil moisture are essential to the stability and integrity of the dunefield. Water balance, groundwater, and soil moisture col-

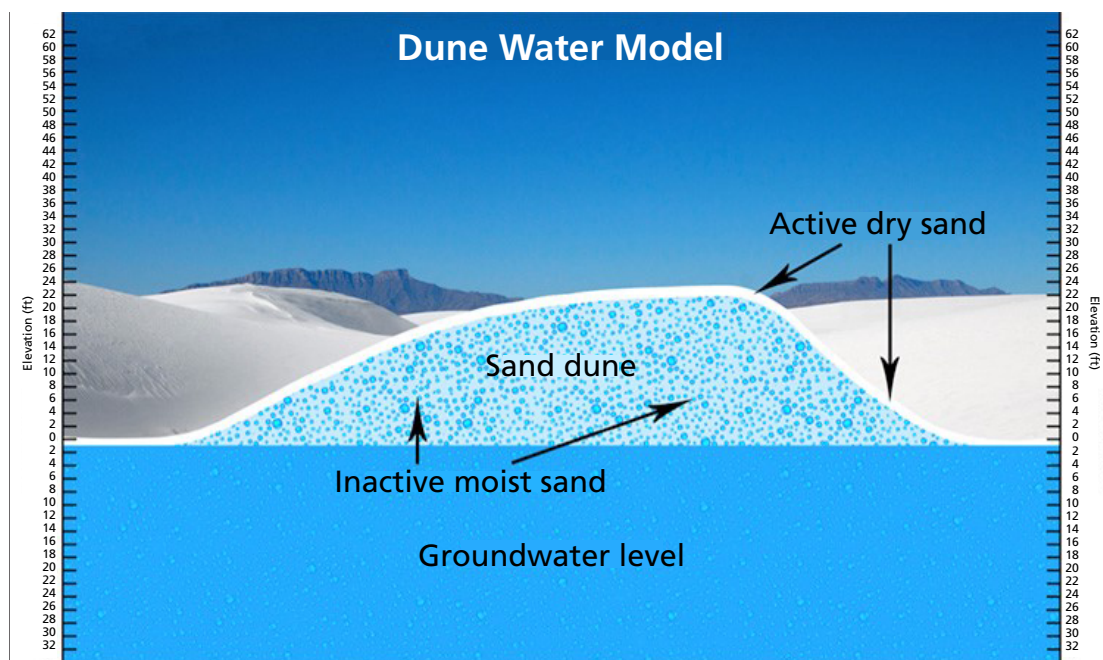


Figure 4. Conceptual model of the relationship between groundwater and moist sand wicked up by capillary forces into a sand dune at White Sands National Monument. NPS graphic.

lectively counterbalance wind energy, and thus are important indices to monitor. Dry winds of 24–27 kilometers per hour are sufficient to transport gypsum particles (White et al. 2015). On the other hand, the electro-mechanical forces of water cohesion and adhesion help particles resist wind energy, keeping them in place and reducing their erodibility. Groundwater levels affect the depth below the surface to which moisture is wicked up into the gypsum sand. This is also a function of cohesion between water molecules and adhesion between water molecules and gypsum particles. This cohesion/adhesion helps capture and retain gypsum particles as they saltate across the dune surface. The subsurface soil is moist in most areas of the dunefield; in some areas, even the surface is moist. A secondary effect of high groundwater elevations is that the proximity of groundwater to the surface helps establish vegetation which, in turn, helps stabilize the dunes in their current location.

Changes in groundwater levels may manifest themselves differently in the dunefield. But in general, if the water table (typically within one meter of the surface) were to fall, there would likely be enhanced surface deflation due to wind, with a corresponding increase in sediment supply and sand-dune growth. Given no concomitant change in the wind regime, these larger sand dunes would migrate more slowly.

If the water table were to rise, then the dune surface, across which the dunes migrate, would also rise in elevation by incorporating sediment from the basal portions of migrating dunes and inducing long-term sediment deposition within interdune areas. Such an increase in the elevation of the stable basal surface would produce a decrease in the supply of mobile sediment and likely produce a decrease in overall dune size. Given no change in the wind regime, these smaller

sand dunes would migrate more rapidly than dunes monitored between 2007 and 2010 (Kocurek et al. 2012).

Because of the close link between moisture and dune stability, changes to the hydrologic processes that create this unique resource (e.g., precipitation, evapotranspiration, and groundwater levels) could jeopardize the White Sands dunefield and the organisms that rely on it. Episodic transport/export episodes may be similarly triggered by extended drought, reducing groundwater levels and negatively impacting the dunefield. Using metrics that could signal changes to the dunefield related to climate change, land development, or other anthropogenic drivers affecting hydrologic processes in the basin would be important early warnings for considering management actions to protect this resource.

1.4.6.2 Surface Water

Lake Lucero, and the small, perennial stream channels that occur in the park and adjacent lands, create a rare aquatic and riparian habitat at White Sands NM. The highly saline Lake Lucero is a remnant of the larger, Pleistocene Lake Otero. The Lake Otero Basin (Lake Lucero locality) is the primary source of gypsum within the White Sands dunefield. The most important perennial streams in the White Sands dunefield are Lost River and Salt Creek, home to White Sands pupfish (*Cyprinodon tularosa*). Because Lost River emerges from a spring flow near a fault on Holloman AFB and flows into the monument during high precipitation events in the Tularosa Basin (which is internally drained) before evaporating, these pupfish periodically enter the park yet are isolated from other populations and any stream network. The riparian area along the streams influences the aquatic habit and creates conditions for a variety of terrestrial organisms that inhabit and visit these areas.

2 Program Goals and Objectives

The goal of this monitoring is to provide park managers with timely, quantitative information on the status of the overall White Sands dunefield system using inexpensive remote-sensing technology. This information will help support data-based, scientific decision-making within White Sands NM and beyond. This protocol will be used in tandem with the CHDN dune dynamics protocol, designed to monitor the dynamics of dune morphology within the system (Smith et al. 2016).

This protocol will establish a monitoring program that can detect and quantify changes in the stability and integrity of the White Sands dunefield. The protocol monitors the entire dunefield—including the monument proper, Holloman AFB, and White Sands MR—and will provide early warning of changes to the entire dunefield. The objectives are:

- To determine if the dunefield is stable (e.g. is increasing or decreasing in size or moving) and
- To determine if the dunefield is maintaining its integrity (e.g., to measure if vegetation and soil moisture are changing over time to evaluate whether the conditions that create and maintain the dunefield are changing).

Specific questions to be addressed include:

- Are the dunefield margins moving or stable?
- Is the overall area of the dunefield changing?

- Is the dunefield centroid moving? If so, at what rate and direction?
- Are there changes to the vegetation (e.g., area inhabited by the specific taxa outlined herein) in the dunefield?
- Are there changes in the soil moisture or water balance that would affect stability or integrity?
- Are proximal (1-cm) and root zone (50-cm) soil moistures changing?
- Is the wetted area of Lake Lucero changing?
- Are the lengths of Lost River and other stream channels changing?

If the answer to any of these questions is yes, then investigations into stabilization processes and status of the gypsum source (e.g., source area size, location, hydrology, or sedimentology) may need to be initiated.

The degree to which park resource staff might be able to manage for changes that are occurring will depend upon the degree of change and the source of the perturbation causing the change. Having long-term trend data to understand how this dunefield functions in dynamic equilibrium (if it is in such a state), is critical before we can determine what is “normal” versus what is a unidirectional change that might be of concern. Only after we begin to understand this system can we then start to address changes.

3 Research Sampling Design

Because this protocol seeks to identify large-scale changes to the entire White Sands dunefield, stability and integrity are of particular importance. The size and location of the dunefield can be used as primary metrics for indexing change in the dynamic equilibrium of conditions and processes that create and perpetuate the dunefield. The location and extent of vegetation within the dunefield indexes the integrity of the dunefield and serves as a secondary indicator of potential issues affecting stability. Therefore, metrics that measure these changes are key to describing and understanding the long-term integrity of the dunefield.

Ascertaining the dynamic equilibrium of this system, and the processes that sustain it, is critical to its long-term protection. If the balance between the sand source and its transport out of the field is altered, drastic changes to the dunefield and its ecosystem may occur. The dunefield may change in size if sand-flux dynamics change. The dunefield may migrate if soil-moisture conditions or wind patterns change. Understanding the parameters of dunefield equilibrium will help us establish a baseline for knowing when processes depart from equilibrium.

Assessing stability and integrity in tandem will allow us to understand and track the interplay of processes and elucidate possible conditions of concern to park managers. Both of these synergistic, complementary components address the hydrology underpinning the dunefield ecosystem. Because soil moisture and water balance are prerequisite to sand stability and the ecology of plants adapted to this unique environment, a change in condition will manifest itself in changes to stability, integrity, or both.

The dynamics governing sediment supply, and its stability and export from the system, need further investigation. Remote sensing can be used to monitor for episodic or rate-of-change alterations in system dynamics. This monitoring gives resource managers the tools needed to:

1. Quantify margin movement affecting location and area,

2. Identify areas needing urgent or emergency investigation for management action,
3. Apply scientific criteria to management practices, and
4. Provide a baseline for modeling of environmental change associated with climate change and regional water demand.

A remote-sensing approach can be used to monitor whether the entire dunefield is changing in size (e.g., increasing or decreasing), and/or if the dunefield is moving or migrating from its current and historical location. Remote sensing can also help assess changes to ecological integrity by measuring aspects of the dunefield, primarily vegetation type and spatial coverage as an index of ecosystem changes. This protocol uses remote sensing and other technological tools, such as GIS, Landsat, ASTER (Advanced Spaceborne Thermal Emission and Reflection), MODIS (Moderate-Resolution Imaging Spectroradiometer) satellite data, EVI (Enhanced Vegetation Index) and NDVI (Normalized Difference Vegetation Index) (see Chapter 4), and NDWI (Normalized Difference Water Index) in conjunction with the network's LiDAR and vegetation monitoring, to achieve its objectives.

The use of remote sensing to monitor changes in boundary conditions between environments is well documented in the refereed scientific literature (e.g., Grigio et al. 2005). The automatic extraction of data from classified remote-sensing images provides an objective way to analyze changes in dune systems through time.

3.1 Definitions of Stability and Integrity

Dunefield characteristics that index changes to environmental conditions that currently support a healthy White Sands dunefield ecosystem will be monitored in this protocol. The long-term stability of the dunefield, and the physical and biotic integrity of the system, each help reveal the current "health" of the dunefield in different ways.

3.1.1 Stability

There is no precise definition of what constitutes a “stable” dunefield, nor is there much historical context for understanding what kinds of measurable, large-scale, noteworthy changes might warrant concern. The term is relative and likely dependent on the specific dynamics of a particular dunefield. Generally speaking, a stable dunefield would be one that persists in location over relatively long periods of time—for instance, at least the length of the Pleistocene.

In the context of the White Sands dunefield, stability refers to the degree to which the dunefield maintains its current size and location/position within the Tularosa Basin, given its internal dynamism: while dunes migrate across the dunefield, these processes occur at a smaller-than-dunefield scale. In short, stability addresses the general question: “Is the general location of dunefield changing?”

Currently, the dunefield as a whole appears to be rather stable, reflecting a dynamic equilibrium. The monitoring conducted in this protocol will help elucidate the movement dynamics of the dunefield in the comparatively short term and, over time, provide a fingerprint of what stability (equilibrium) looks like for the White Sands dunefield.

Based on our limited knowledge of gypsum dunefield dynamics, dunefield stability may be described as locationally static (i.e., never moving outside its current boundaries) or locationally dynamic, yet still relatively stable (i.e., reflected as a dynamic, serial oscillation in which the periodicity of natural changes to the boundaries ebb and flow over time within a limited area—unless a longer-term, destabilizing force is introduced into the system). Geology, geography, climate and weather, edaphic properties of gypsum sand, and groundwater are all intractably linked to the sustainability of dunefield stability.

3.1.2 Integrity

Integrity of the dunefield is defined as “the state whereby abiotic and biotic processes are identifiably intact and in sufficiently good condition to create and maintain the dunefield roughly in its current ecological state.”

Intact integrity assumes that the structure (e.g., location, distribution, juxtaposition, size, and composition of plants) and function (using specific plant species as habitat-specific sentinels) of the community operate within the boundaries of natural variation under current environmental conditions (with the assumption that the current state helps delineate the appropriate, high-quality state within that range of natural variation).

Integrity addresses the dunefield-specific environmental conditions to which endemic plants and animals have adapted. Loss of these properties could result in habitat loss for many endemic species. Detecting changes in these dunefield-adapted bioindicators through monitoring could elucidate broader changes in the ecosystem and portend a destabilizing process that could undermine the entire dunefield.

3.1.3 Interconnection through Soil Moisture

Stability and integrity are intertwined in the White Sands dunefield through a shared reliance on soil moisture, largely associated with groundwater levels. Soil moisture affects both stability and integrity of the dunefield simultaneously, as one index. If surficial soil moisture declines, the dunefield becomes destabilized and the biotic communities that rely on these habitats are affected, or vice versa. Thus, identifying changes in one component may provide clues that the other is changing in tandem. For instance, a compromised groundwater resource may cause a chain reaction, affecting both plant community dynamics (i.e., species distribution and abundance), and sand transport dynamics.

Dunefield stability is strongly linked to surface and near-surface moisture. The unique physical properties of sand allow groundwater to be wicked up into the sand by capillary action, keeping sand located just under the surface moist (Kocurek and Havholm 1994, Kocurek et al. 2007, Scheidt et al. 2010). This is important because gypsum has a lower specific gravity than silica-based sand, allowing it to be transported more easily by wind. Wind speeds of 15–17 mph can mobilize gypsum particles (White et al. 2015). Soil

moisture reduces transport both within the dunefield and off-site. The wicking process also makes soil moisture more readily accessible to plants across the dunefield.

It's unclear which may change first if the sediment/moisture/wind balance is compromised: stability or integrity. Because vegetation is key to monitoring the integrity of the dunefield, and is inextricably linked to soil moisture, it may hold the key to detecting changes early. Soil moisture is also linked to dune morphology, dune movement, and groundwater dynamics, but changes in these parameters may manifest more slowly. Therefore, one integrative measure—soil moisture (and by extension, water balance)—will be monitored as part of this protocol. Changes in precipitation or evapotranspiration as artifacts of climate change, or in groundwater levels as artifacts of development within and outside the Tularosa Basin, are of particular concern.

3.2 Metrics

Only long-term monitoring of environmental conditions can help us ascertain the dynamism of the White Sands dunefield, and the quality of its environment. Specifically for this purpose, we consider the processes that create sand and stabilize dunes as creating the conditions under which the dunefield's plant and animal communities thrive.

Data collected on the White Sands dunefield will aid our understanding of the entire field, including areas outside the park boundary. Stability of the dunefield is best assessed for the entire field, because of the dynamic nature of shifting dunes and gypsum sheets. Monitoring changes in “condition-related” dunefield characteristics will assist in tracking the integrity of the entire dunefield and provide foresight into impending conditions (such as drought) that could affect stability. Some changes in vegetation are expected due to the dynamic nature of shifting dunes and variation in climate. Analysis of historic and current conditions beyond the park boundary is imperative to protect the health of the dunefield within the park boundary due to linked climate, hydrology, and wind effects that interact at broad spatial scales.

3.2.1 Measuring Stability: Dunefield Characteristics

The White Sands dunefield presents a bit of a scientific mystery: Why does the dunefield remain in place, and why isn't the dunefield overrunning Holloman AFB to the east, on the prevailing downwind side? Moreover, even as sand continues to be transported into the dunefield from Alkali Flat to the west and is ultimately transported away to the east, the dunefield's size and relative location have remained fairly stable through time (Figures 5 and 6). In fact, over at least the last 60 years, the dunefield's margins have remained in place, maintaining relatively linear and abrupt transitions from mobile gypsum dunefield to Chihuahuan desert scrub dominated by in-situ soil processes and native vegetation. Yet within the central part of the dunefield, dunes can migrate tens of meters per year—primarily in a west-to-east direction (Ewing and Kocurek 2010; Kocurek et al. 2010). This seeming contradiction between the internally active dunes and the

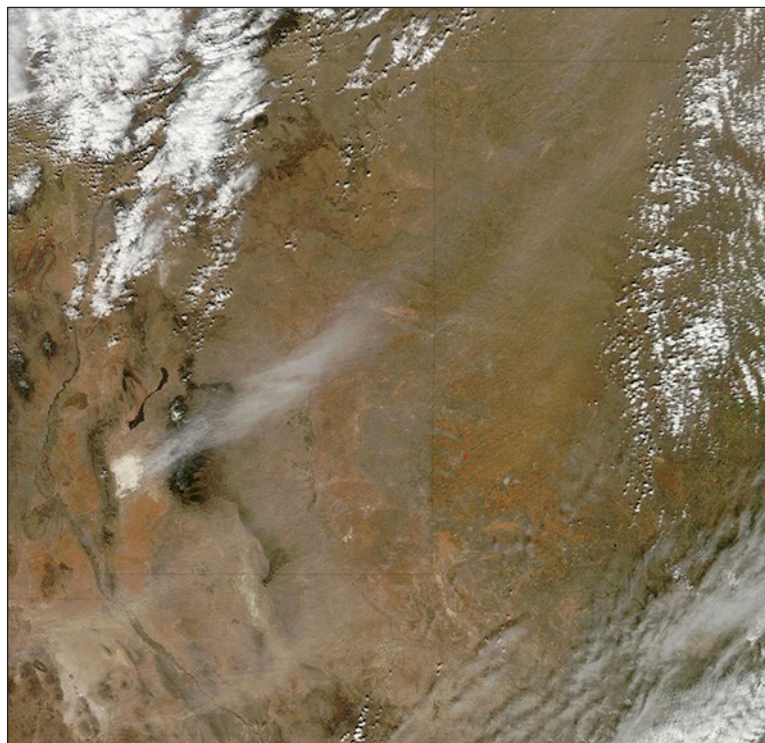


Figure 5. NASA image showing gypsum-sediment particles from the White Sands dunefield (center left) blowing into the panhandle of Texas and Oklahoma. Predominant prevailing winds across the dunefield are southwest-to-northeast, February 28, 2012. The lower-left (southwest) portion of the dunefield is the location of Lake Lucero and Alkali Flat, the source of gypsum for the field. Source: https://earthobservatory.nasa.gov/NaturalHazards/view.php?id=77294&eoqn=image&eoci=related_image.



Figure 6. Closer NASA image of the same dust storm, photographed at a different time and showing sand being carried beyond the east margin of the White Sands dunefield, February 28, 2012. Source: <https://earthobservatory.nasa.gov/NaturalHazards/view.php?id=77775&eoan=image&eci=morenh>.

overall stability of the dunefield margins remains poorly understood.

The general stability metrics evaluated in this monitoring process are:

1. Change in size of the dunefield from a predefined reference,
2. Change in location and size of the dunefield based on the location of the perimeter boundary along each side of the dunefield (N,S,E,W), and
3. Change in the centroid of the dunefield from the initial reference point. The first metric is concerned with whether the White Sands dunefield is contracting or expanding. The second and third are concerned with whether the dunefield is moving, migrating, or shifting.
4. Change in area of Lake Lucero through time.
5. Change in the area of parabolic dunes through time.

These metrics are described below and summarized in Table 1.

3.2.1.1 Dunefield Size: Area

Dunefield area is derived from the polygon of the margin perimeter encompassing the entire field. Whereas changes to perimeter margins indicate dunefield movement, it is unclear whether those movements are uni-

directional or actually represent oscillations in dunefield perimeter. Monitoring area will provide a clear signal on losses or gains in the dunefield size.

3.2.1.2 Dunefield Perimeter Margins (N,S,E,W)

This metric indexes changes in the location of the dunefield margins relative to the four ordinal directions (N,S,E,W). The perimeter-margin metric is designed to be the most sensitive measure in identifying whether the dunefield is moving—and if so, how quickly. Long-term monitoring will, over time, reveal the “normal” oscillation dynamics (i.e., ebb and flow) of sand along the dunefield margins. Given that the dunefield has been in its general current location for decades, the assumption is that the conditions under which the dunefield persist have been stable throughout this time period. Should those conditions change, movement of margins may become apparent, serving as early warning of potentially more significant changes underway. Pre-selected, standardized points along each perimeter boundary will be monitored in each time series image to ascertain the degree to which the boundary has moved, and in which direction.

3.2.1.3 Dunefield Centroid

The centroid is a powerful index of overall dunefield movement representing the center of the entire field. It provides an indicator of any potential shift of the overall dunefield (as opposed to perimeter-margin movements). In contrast to the dunefield margins, which may fluctuate per some dynamic equilibrium relative to their specific location, changes in the centroid would signal a more pronounced fundamental change to the dunefield and take longer to elucidate a larger-scale change. Thus, changes in the centroid would suggest a more significant change to the field, indicating that a larger process affecting the dunefield is underway. Moreover, the index gauges the ebb and flow of dunefield central tendency, which is ultimately controlled by physical forces, hydrologic condition, sediment source, and stabilizing effects of vegetation—also suggesting larger scale shifts in system dynamics.

Table 1. Metrics that assess the stability of the White Sands dunefield using dunefield characteristics.

Metric	Metric Description	Rationale	Measure	Requirements
Dunefield Size: Area	Metric designed to index the overall size (area) of the dunefield.	Changes to perimeter margins index dunefield movement, but it is unclear if those movements represent an actual true dunefield shift or are merely oscillations in dunefield location. The overall area measurement would provide a clear signal of changes in the dunefield size.	Change in area through time.	GIS exercise using high-resolution geo-referenced remote sensing layer available within 5-year (maximum) time frequency. Landsat or NAIP.
Dunefield Perimeter Margins (North, South, East, West)	This metric is designed to index directional changes in the location of the dunefield. Along each perimeter margin (N,S,E,W), 100 pre-determined points will be monitored over time to ascertain perimeter boundary movement in a particular direction. Movement will be denoted as (+) or (-) for each point relative to each margin for each subsequent time sequence comparison. Net differences in location for each point, and for each ordinal margin, will be tracked through time, along with the point having the largest (+) and (-) movement individually along a particular margin.	Indexing changes in the location of the dunefield perimeter margins relative to the four ordinal directions will help identify whether the field is moving and the rate of movement.	Net change in the ordinal location of each respective dunefield margin (N,S,E,W).	GIS exercise using high-resolution geo-referenced remote sensing layer available at a 5-year (maximum) recurrence time frequency. Landsat or NAIP.
Dunefield Centroid	The centroid represents the calculated geographic center of the entire dunefield. The centroid calculation uses all 400 margin points in the Dunefield Perimeter Margin metric described above (100 each for North, South, East, and West margins).	The centroid is a less-sensitive measure of dunefield movement but provides a more powerful general index of overall dunefield movement. While margins may oscillate in some dynamic equilibrium by moving forward and backward through time, changes in the centroid pinpoint a larger-scale change to the field.	Change in calculated location of centroid over time. Metric is the geographic center of all 400 points derived from the margin locations.	GIS exercise using high-resolution geo-referenced remote sensing layer available at a 5-year (maximum) recurrence time frequency. Landsat or NAIP.
Lake Lucero (Gypsum Source) Area	Metric designed to index the area of Lake Lucero, the source of sand on Alkali Flat.	Lake Lucero and corresponding Alkali Flat is the source of gypsum for the White Sands dunefield.	Change in area through time.	GIS exercise using high-resolution geo-referenced remote sensing layer available within 5-year (maximum) time frequency. Landsat or NAIP.
Location and Area of Parabolic Dunes	Subset of dunefield area referencing a particular morphological type of dune associated with vegetation which helps to create this dune type.	The Barchan-Parabolic Transition occurs with declining sand flux that triggers an abrupt increase in vegetation density, which in turn leads to changes in groundwater depth and salinity—showing that aerodynamics, sediment transport, and ecohydrology are tightly interconnected in this landscape (Jerolmack et al. 2012).	Change in location of the transition zone and area of parabolic dunes through time for the Greater White Sands dunefield.	GIS exercise using high-resolution geo-referenced remote sensing layer available within 5-year (maximum) time frequency. Landsat or NAIP.

3.2.1.4 Lake Lucero (Gypsum Source)

Area

Lake Lucero is the remnant of Lake Otero and the subsequent gypsum terraces that were created as water levels declined including Alkali Flat; the current main source of sand to the dunefield. Changes in the moisture regime of the system, as has occurred over time, would also manifest changes to sediment delivery to the dunefield and be discernable via the area of Lake Lucero. During drought, the lake area would decline in size and be a harbinger for changes in dunefield stability.

3.2.1.5 Location and Area of Parabolic

Dunes

Parabolic dunes are one set of two primary dune types that transition as sand migrates across the dunefield (Smith et al. 2016). Transverse, barchanoid, and barchan dunes are all forms of crescentic dunes, in which the ends of each individual dune are located downwind. Parabolic dunes, the most evolved, are reverse of that, and are usually found near the margin of the dunefield. Change in the area of these dunes suggests that the dune dynamics are shifting and investigation to better understand what is happening is warranted.

3.2.2 Measuring Integrity: Vegetation Characteristics

In the White Sands dunefield, vegetation is a manifestation of physiological and anatomical adaptations of the plant, linked to the soil-moisture characteristics that provide the foundation for the existence of the dunefield. Changes to those dynamics can be ascertained by monitoring vegetation that directly indexes integrity of the dunefield, and indirectly indexes potential emerging problems of stability. In short, the vegetation present is the functional consequence of the environmental conditions to which vegetation responds.

Vegetation provides one measure of ecosystem integrity (i.e., condition) by assimilating a suite of hydrophysical characteristics and climate conditions essential to maintaining the White Sands dunefield and the organisms that lie at the intersection of physical and

biological processes in that unique environment. Integrity of the dunefield is a measure of health as it pertains to the ability of abiotic processes (e.g., soil moisture, groundwater levels, water balance) to interact and create habitats for vegetation. Integrity indexes whether the vegetation community is stable (signaling the physical environment is relatively stable) or changing (suggesting physical environmental flux). If the composition of vegetation in the dunefield persists, consists of native endemic and historical vegetation, and is maintained over time, then processes and ecosystem components are considered to exhibit high integrity. Conversely, if there are changes in the vegetation, then integrity may have been compromised.

The integrity of the White Sands dunefield will be monitored using a combination of vegetation and soil-moisture/water-balance metrics (see Section 3.2.3). While overall greenness calculated for all species combined is desired, species-specific analyses of native and exotic plants are also important. Of particular ecological interest are those species thought to be indicators of change relative to groundwater availability close to the dune surface.

The secondary metrics for vegetation proposed below (see Section 3.2.2.2) are untested at this point and will be implemented only if feasible. If implemented, future analyses should test whether particular types of vegetation can be quantified and used for long-term monitoring. Monitoring a few key species on the dunefield, including an aggressive exotic, will speak to the dunefield's long-term integrity. Staff at White Sands NM identified these species primarily because of their ability to provide insight into groundwater dynamics of the dunefield. They are also useful indicators of system stability, because moisture near the surface is important to sand transport and retention dynamics. Should groundwater levels drop and dunes become dry, it is believed that deflation will occur as wind transports sand from the dunefield.

Metrics that would provide insight into changing environmental conditions to which vegetation responds are described below and in Table 2.

Table 2. Metrics that assess the integrity of the White Sands dunefield using vegetation.

Metric	Metric Description	Rationale	Measure	Requirements
Total Vegetative Cover (area)	Area of all vegetation in the White Sands dunefield.	The biological integrity of the dunefield can be indexed by measuring changes in vegetation types in the dunefield. Vegetation is key to the animals that inhabit the dunefield area. They also interact with blowing sand to create varying dune types and microhydrologic conditions.	Change in areal cover over time.	OPTION 1: Generate a set of permanent image plots of a specific size and shape that could be validated on the ground as needed for composition (change in shrub/tree species, invasives) and structure (height and burial). Could tie in with uplands vegetation monitoring. OPTION 2: Delineate a suite of vegetation patch polygons and cue in perimeter changes and canopy density and composition (plotless).
Cottonwood Area	Measure of the area of all cottonwood (<i>Populus</i> spp.)	Major tree species found in the White Sands dunefield. Associated with high freshwater water tables, cottonwoods create significant habitats and alter sand migration across the dunefield.	Change in areal cover over time.	same as above
Cottonwood Saplings/Seedlings Area	Measure of the area of cottonwood (<i>Populus</i> spp.) seedlings and saplings.	Cottonwood trees need higher groundwater levels for their seeds to germinate and survive. Because the dunefield dunes migrate west to east, groundwater availability and quality change in the migrating interdunal areas (water in interdunal areas is more saline). Cottonwood trees send out suckers in the White Sands dunefield in the direction of dune migration in order to perpetuate.	Change in areal cover over time.	same as above
Grasses Area: Alkali sacaton	Measure of the area of alkali sacaton (<i>Sporobolus airoides</i>) across the dunefield.	Alakli sacaton is tolerant of higher salinity. It occurs primarily in interdunal areas (lower topography), where surficial groundwater is more saline. Change in the area of this grass would index changes in groundwater quality.	Change in areal cover over time.	same as above
Grasses Area: Little bluestem grasses area	Measure of the area of little bluestem (<i>Schizachyrium scoparium</i>).	Little bluestem is found primarily near the tops of dunes in White Sands NM, where groundwater is less saline, thus indexing water quality conditions and changes in dunefield morphology. Its distribution is reciprocal to that of alkali sacaton, which occurs in low, interdunal areas.	Change in areal cover over time.	same as above
Grasses Area: Needle grama area	Measure of the area of needle grama (<i>Bouteloua aristodoides</i>).	The only other major vegetation type found in the White Sands dunefield.	Change in areal cover over time.	same as above
Grasses Area: Indian ricegrass (<i>Achnatherum hymenoides</i>)	Measure of the area of Indian ricegrass (<i>Achnatherum hymenoides</i>).	Interdunal areas, particularly in parabolic dunes	Change in areal cover over time	Same as above
Tamarisk area	Measure of the area of tamarisk (<i>Tamarix</i> spp.) cover.	An invasive exotic plant that dramatically alters the dunefield and its integrity. Tamarisk creates conditions where dunes change morphology, thus interrupting the natural environment for endemic plants and animals. Tamarisk creates sand pedestals where blowing sand accumulates around tamarisk plants that keep growing higher above the accumulating sands.	Change in areal cover over time.	same as above

3.2.2.1 Area of Total Vegetation Cover

This metric uses MODIS-NDVI/EVI (i.e., greenness) to ascertain overall changes in vegetation across the dunefield (see SOP #4). Vegetation has a distinct spectral signal that allows it to be quantified against generalized land-cover signals. In particular, bands of red, green, blue, and infrared are of value in indexing vegetation. Two commonly used indices to assess total vegetation cover are NDVI and EVI. Using MODIS satellite data, the NDVI indexes terrestrial photosynthetic activity. The EVI indexes structural vegetation properties. Munson and others (2016) provided a compelling use of MODIS EVI to assess vegetation trends in the Mojave Desert, with large declines in perennial vegetation cover in the northwestern portion and increases in the northeastern and southeastern portions. The authors demonstrated the ability to quantify changes of perennial plant cover to an entire desert.

3.2.2.2 Species-specific Indices of Vegetation (Future Consideration)

Secondary metrics for vegetation are proposed here *only if feasible and are untested at this point*. If feasible, future analyses should test whether particular types of vegetation can be quantified and used for long-term monitoring.

Groundtruthing is essential to this effort to assess changes in vegetation, and would be prerequisite to ascertain its feasibility. Subject-matter experts at the park or network will work with the GIS analyst to ensure areal measurements are concurrent with remotely sensed estimates. This will be addressed in a future revisioning of this protocol, once tested.

Cottonwood Area—. Cottonwoods are associated with high freshwater water tables. They create significant habitats and alter sand migration across the dunefield. NAIP (National Agricultural Imagery Program) remote-sensed images would make it feasible to count the number of cottonwood trees in predetermined, randomized grids placed on the images.

Cottonwood Seedlings/Saplings Area—. Reductions in recruitment of young cottonwoods, in particular, could suggest reduced

groundwater levels or changes in groundwater quality. Young trees might be more problematic, in that their remotely sensed signature may be more difficult to detect, thus requiring preliminary work to assess the feasibility of this metric.

Grasses (Species-specific Area)—. If groundtruthing is possible, several grasses are of ecological importance, but analysis to assess the feasibility of using them is required. Because grasses index soil moisture/water conditions, they are key to monitoring ecological response using remote sensing. Changes in the abundance/density of these grasses would indicate changing groundwater levels or water quality. These species include:

- Alkali sacaton (*Sporobolus airoides*)
- Little bluestem (*Schizachyrium scoparium*)
- Gyp grama (*Bouteloua breviseta*)
- Indian ricegrass (*Achnatherum hymenoides*)

Tamarisk (Tamarix sp.) Area—. Tamarisk, also known as saltcedar, is an invasive exotic plant introduced to New Mexico in the 1800s. It is adapted to a wide range of environmental conditions and can outcompete native vegetation and grow in dense stands. Its high consumption of water and ability to tolerate more saline water supplies makes it adaptable to the White Sands dunefield. In addition to outcompeting native plants, tamarisk can withstand substantial burial by continuing to grow above dunes and re-sprout. As a result, denser stands of tamarisk affect dune formation and transport of sand across the dunefield.

3.2.3 Measuring Integrity: Water Resources

The most important resource in any ecosystem is water—especially in the desert. Water resources are vital to the integrity of the White Sands dunefield and its ecosystems. Soil (sand) moisture helps stabilize the dunes and is essential for vegetation. The dunefield's water balance is relevant to all water resources there. Surficial waters, including Lake Lucero and streams, are an important

part of the overall water and dune system, and are also essential parts of the ecosystem. Metrics delineated here will provide insight into the status of the overall integrity of the system.

In arid regions, ephemeral stream morphology and riparian areas can provide sensitive indicators of environmental stressors with biological implications. Basin- and channel-scale stressors are important to resource managers, particularly when assessing the stability of resources sensitive to climate change. Remotely sensed monitoring can provide insights into changes that may be a result of:

- climate change,
- alterations of the hydrological system (for example, drawdown of the water table from agricultural use or desalinization from invisible use),
- anthropomorphic alteration of the drainage system,
- changes in riparian vegetation and ecosystems that may result from both natural and anthropomorphic change (for example, the removal of tamarisk),
- change in tectonics, or
- changes in sediment supply.

Riparian areas are important because they are delicate, restricted, and host rare habitats. For example, the White Sands pupfish (*Cyprinodon tularosa*), listed as threatened by the State of New Mexico, is restricted to two small streams (Lost River and Salt Creek) and just two springs (Malpaís and Mound). Riparian areas that show stress could indicate water quantity problems or other habitat-degrading perturbations.

Metrics that would provide insight into changing water conditions are described below and in Table 3.

3.2.3.1 Soil Moisture

The importance of soil moisture to the White Sands dunefield cannot be overstated. Kocurek and Havholm (1994) have classified the dunefield as a “wet aeolian system” where relatively high soil moisture affects sediment-transport dynamics. As has been described, the relatively high groundwater table, in com-

bination with interstitial physics of gypsum grains, creates capillary water movement, drawing water up into the dune subsurface through the gypsum-sand interstices. It is essential for the stability of the dunefield and the integrity of the ecosystem.

Soil moisture can be indexed using technologies that exploit the reflective intensity of moisture being evaporated from the soil (sand) surface. One approach, using MODIS or ASTER radiometry to estimate soil moisture in the dunefield, has already been successfully deployed at the monument for NDWI (Figures 7–8) (from Scheidt et al. 2010). MODIS and ASTER collect coincident reflected and emitted radiance, but at much different spatial, temporal, and spectral scales (Scheidt et al. 2010). Generally, ASTER images are collected every 16 days and MODIS twice every 24 hours for the White Sands study area. The application showed significant relations among soil erosion, soil moisture, and thermal inertia derived from images. Other image analyses can estimate near-surface soil moisture, as this layer is the most important estimate relative to sand transport at White Sands (Figure 9). Estimates from RADARSAT (radar satellite) images can explain up to 85% of the variation in actual watershed level-soil moisture (Thoma et al. 2006).

Daymet gridded weather data (<https://daymet.ornl.gov/>) will be the standard source of data for soil moisture and water balance (Thornton et al. 2018). Daymet is a daily, 1-kilometer, gridded climate dataset used to calculate water balance using a customized model that runs on a single grid cell daily time series selected from the centroid of the dune field. Daymet is created from local weather station data, when available, and interpolated in space and time to fill in gaps. In this respect, the water-balance model is run using data from local stations. Missing station data and spurious data values are adjusted in the Daymet algorithm to minimize the effect of errors in the station data for any given site.

Long-term soil-moisture monitoring plots will provide diagnostic information about the ability of the dunefield to sustain its current vegetation (see SOP #5). They may also

Table 3. Metrics that assess the integrity of the White Sands dunefield using water resources.

Metric	Metric Description	Rationale	Measure	Requirements
Soil Moisture	Index of soil moisture.	Moisture is key to the stability and integrity of the White Sands dunefield. Soil moisture is the key component to stabilizing the dunefield.	Change in soil moisture as detected by remote sensing.	OPTION 1: Use of Advanced Spaceborne Thermal Emission and Reflection (ASTER) (Scheidt et al. 2010). OPTION 2: Panchromatic band image density corresponds to soil moisture. OPTION 3: Normalized Difference Water Index derived from MODIS imagery
Water Balance	Index to assess net water balance integrating precipitation and evapotranspiration.	Changes in climate are expected to affect precipitation and evapotranspiration trends, which ultimately affect the stability of the White Sands dunefield.	Need precipitation and evapotranspiration metrics from local weather stations.	Calculation using the water balance model for the area encompassing the White Sands dunefield.
Lake Lucero Area	Area of the margin of Lake Lucero.	Lake Lucero is the repository of the eroding salts (gypsum) from the surrounding mountains and is the source of gypsum for the White Sands dunefield.	Change in lake surface area over time.	Mean perimeter value derived from 4 Landsat images (June, September, December, March).
Length of Lost River	Length of stream.	The only measurable surficial freshwater in White Sands NM. Changes in groundwater levels may significantly impact this resource and the endangered endemic White Sands pupfish (<i>Cyprinodon tularosa</i>).	Change in length of perennial stream over time.	Length derived from Landsat images.
Lost River Riparian Area and Width of Riparian Corridor	Area and width of riparian corridor.	Riparian corridor is a rare and crucial habitat type within the dunefield. Changes in its size will portend changes in stream conditions and specific habitats that it creates.	Change in area and width of riparian corridor over time.	Area derived from Landsat image.

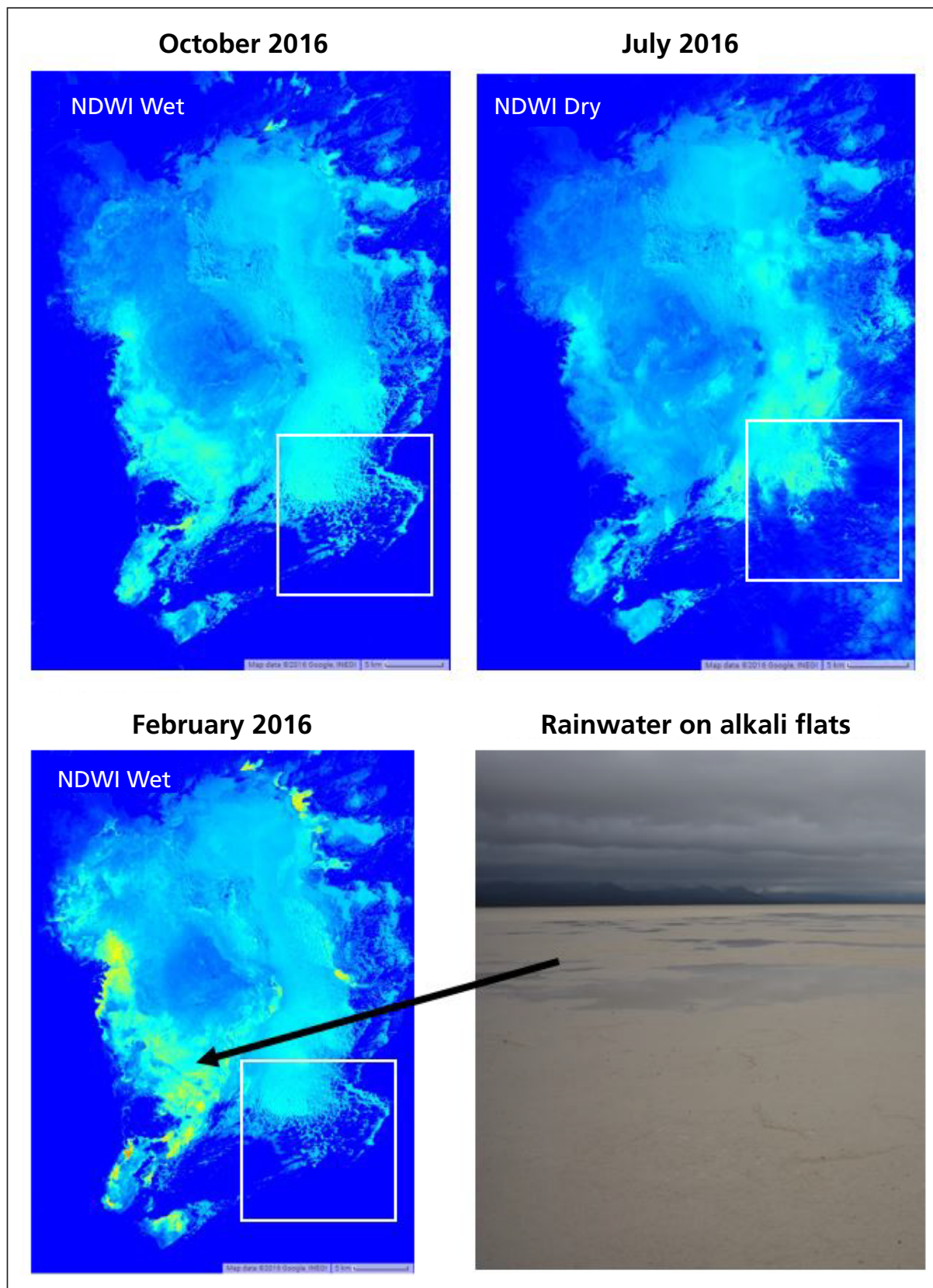


Figure 7. Normalized Difference Water Index (NDWI) data for a typical dry period (July 2016, right) and wet periods (February and October 2016). The smaller box denotes an area where parabolic dunes can be seen in wet periods. As dunes dry, they begin to fade.

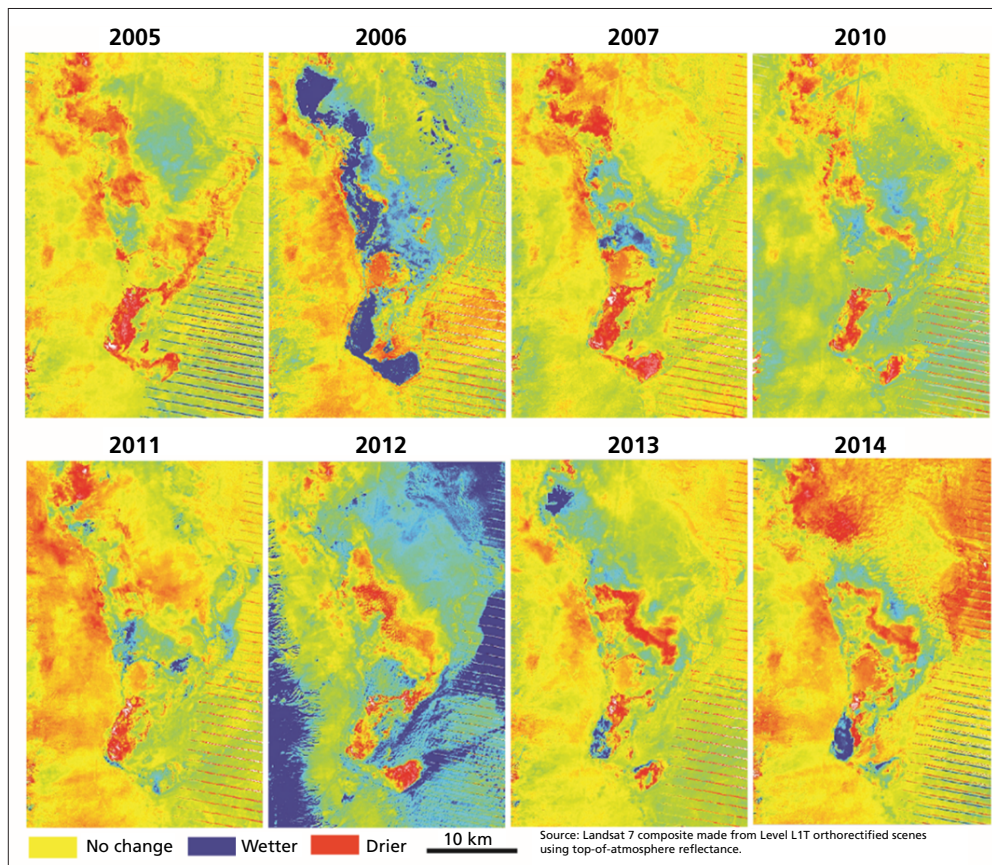


Figure 8. Difference in moisture, first week in December 2005–2014, compared to 2015 (NDWI 8-day composite).



Figure 9. The water table is less than one meter below the White Sands dunefield in most areas, allowing water to be wicked up into the dunes. The high water table helps keeps hold the soil moisture in the dunes. It also results in flooding during large rain events, and in surface puddling in winter, when evapotranspiration is reduced.

provide a covariate for analyses should the vegetation community change over time, water quality notwithstanding. Paired with water balance (see next section), soil-moisture metrics will provide clear diagnostic, early warning measures of changes to the integrity of the dunefield. This monitoring will rely on the weather stations currently running at White Sands, with the anemometer and a soil-moisture probe (e.g., theta probe) providing crucial inputs.

3.2.3.2 Water Balance

Monitoring water balance in the White Sands dunefield can provide insight into long-term changes occurring in both vegetation and factors that affect soil moisture. The balance of precipitation and evapotranspiration (i.e., “water balance”) is a significant factor influencing species-specific plant physiology that in turn affects plant communities in terrestrial ecosystems. Water balance is an assessment of the relative proportions of water inputs into, and outputs from, an ecological system (Gleick 1987). Lutz and others (2010) demonstrated the value of a water-balance model in Yosemite National Park, modifying it from a model originally developed by Dingman (2002). The climate submetrics that go into calculating water balance all provide insight for monitoring long-term changes to

the climate of the White Sands dunefield. Water balance calculated for White Sands NM from 1980 to 2015 (Figure 10) shows a trend of declining soil moisture corresponding to declining precipitation and increasing temperatures. Water needs of vegetation not supplied by soil moisture when soils are dry is called deficit. Deficit, which has increased since 1980, may affect both the vegetation and soil-moisture levels necessary to ensure long-term stability and integrity of the dunefield.

3.2.3.3 Lake Lucero Area

The size of Lake Lucero is important to monitor because changes in its water elevation can signal a shift in climate or in groundwater dynamics—both critically important for the long-term stability of the dunefield’s dynamic processes. Understanding the persistence, extent, and flow dynamics of the lake and the dunefield’s perennial streams (see Section 3.2.3.4) is essential to protecting riparian habitat in the White Sands dunefield.

3.2.3.4 Length of Lost River and Salt Creek

Because the habitat provided by Lost River and Salt Creek is vital to threatened White Sands pupfish (*Cyprinodon tularosa*) and other wildlife that require a surface water source,

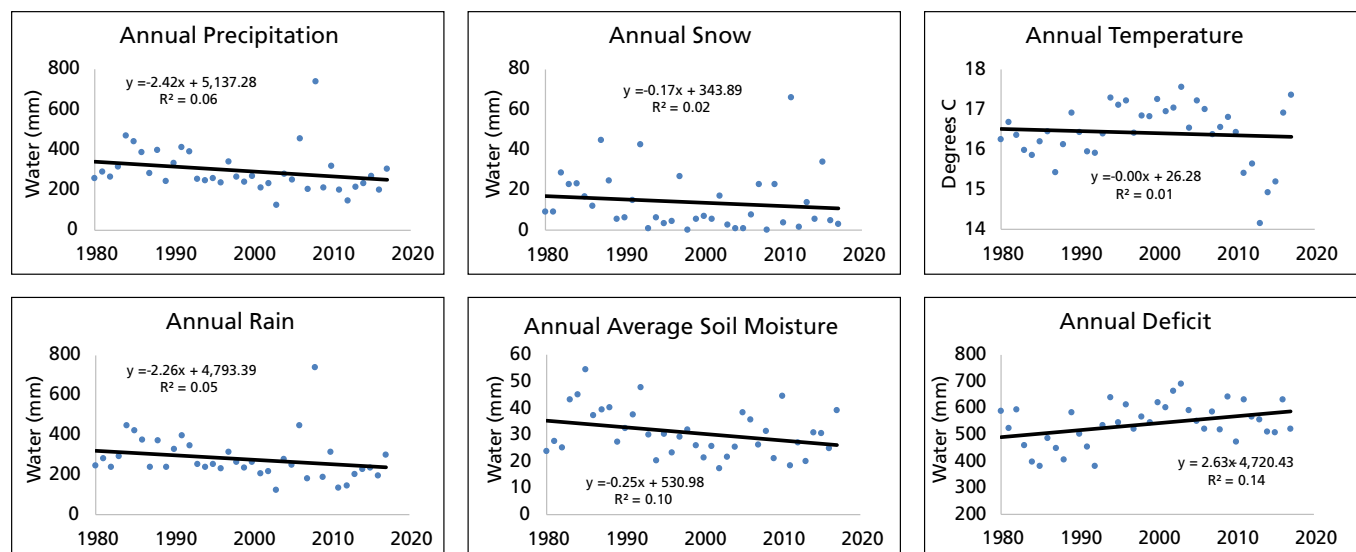


Figure 10. Annual water balance time series for White Sands National Monument headquarters, 1980–2017. Climate data are from Daymet to minimize influence of missing data (<https://daymet.ornl.gov/>). Water balance variables were obtained by passing climate data through the water balance model, assuming 100 mm soil water holding capacity in the top meter and a flat, unshaded surface (Thoma unpublished).

monitoring the length of both streams using remote sensing can provide a general index of the persistence of White Sands pupfish habitat and is crucial to understanding the integrity of the dunefield, reflecting groundwater levels as a water resource.

3.2.3.5 Lost River/Salt Creek Riparian Area: Width of Riparian Corridor

Riparian areas in desert ecosystems are important habitats that create islands of biodiversity in an otherwise stark environment. Demarcation of riparian areas under these conditions is quite straightforward, and changes to the riparian area signal changes to the hydrologic processes that are so vital to the stability of the White Sands dunefield. Moreover, the habitats created allow a greater suite of organisms to exist. Should these habitats decline, many organisms that rely on them would cascadingly decline, as well.

3.3 Additional, Covarying Data (not collected in this protocol)

Separate from this protocol, additional monitoring efforts at White Sands NM will provide supplemental data addressing issues linked to stability and integrity. This monitoring should be consulted during analyses of data from this protocol. These metrics include weather/climate and groundwater.

3.3.1 Weather/Climate

Weather stations relevant to the White Sands dunefield include the following:

- one co-located within the LiDAR study area,

- one positioned immediately upwind of the dunefield, and
- one located at Holloman AFB, approximately 14 kilometers from the LiDAR study area. This station may be used to calibrate historical data from Holloman AFB once enough data have been collected.

Our data come from Daymet (<https://daymet.ornl.gov/>), a grid-based system that takes relevant weather data from proximal weather stations and creates composite weather data for each grid pixel on the nationwide grid (see SOP 5 and SOP 5, Supplement C). In this way, if one weather station had missing data, a data interpolation is made using the other proximal weather stations. Daymet automatically harvests these data and uploads them to the Daymet site.

3.3.2 Groundwater

Groundwater monitoring is ongoing, and will continue. At minimum, monitoring will follow the network's monitoring protocol (Filippone et al. 2014). It may also include data collected for other park-based projects. Twenty-two groundwater monitoring wells and piezometers were installed in the park between 1997 and 2010. The piezometers are located within the LiDAR study area. Data from the water-level sensors is continuous, and can be automatically uploaded to a computer.

4 Remote-Sensing Assessment Techniques and Technologies

4.1 Dynamic Nature of Research Technologies

This protocol describes image analysis using particular remote-sensing image series. A wide variety of satellite-image options, processing software, and computers capable of undertaking these types of analyses are currently available. Yet remote sensing is a field with new technologies, satellites, and computational abilities that rapidly change. Drone technology represents just one rapidly evolving remote-sensing opportunity. This and other new technologies will offer new opportunities for monitoring and analysis, and should be embraced where compatible within the context of the long-term monitoring objectives described in this protocol.

During these transitions, particular focus on quality control and continuity of the data being analyzed needs to be employed to ensure that future observations can be seamlessly integrated with past observations for a continuous time series. This protocol is a framework from which to conduct serial image analysis. It describes an initial, core set of metrics with which to index stability and integrity and focuses more on those metrics than on detailed discussion or debate about the particular tools being used to measure them.

Each time these analyses are conducted (at each five-year and decadal rotation), the analyst will need to evaluate the efficacy of the tools available at that time. It is likely that the specifications outlined in this protocol will have changed by the time future analyses are conducted.

4.2 General Design

The overall design for this protocol is outlined in Figure 11, which shows the parallel paths of both CHDN dune protocols. This protocol will utilize time series-based, multi-spectral imagery derived from remote sensing to quantify changes in the physical properties of the landscape—metrics that index

changes in dunefield stability and integrity. Current source data include various remote-sensing image series (e.g., Landsat 5, 8, NAIP, MODIS), different image bands, and different levels of resolution specifically relevant to particular questions being answered. Other remote-sensing data sources are also open for consideration, subject to evaluation.

One benefit of this remote-sensing approach is that image analysis can and will be applied retroactively to historical images, and additional questions and modifications to approaches can be adapted. For instance, if a portion of the dunefield shows movement in a particular direction, it will be possible, through additional analysis, to track that area through time in an attempt to discern the pattern and rate of change. It may also be possible to use higher-resolution imagery for finer detailed analysis and perhaps elucidate the cause of the change. Moreover, other sources of remote images can be added to expand the scope of the monitoring if desired.

The project will unfold in three phases. Phase I will focus on acquiring a robust reference set consisting of image sequences. These data will be used to train the model. Where possible and necessary, data collected in the field will be matched with remotely sensed data and linked per the objectives as groundtruthing. These reference data are fundamental and indispensable for a scientifically valid remote-sensing study—particularly for studies used to support management decisions (Kennedy et al. 2009). Fixed-point building locations in the park will be used in each imaging analysis sequence during groundtruthing. Building and distances between them and roadways are stable known points, thus their locations are known and fixed. Measurements will be corrected for any imaging errors relative to changes in measurements from those locations.

Phase II will derive time series data collected from images and archived. The initial time series data will provide the baseline for evaluating changes in the system. It will also provide

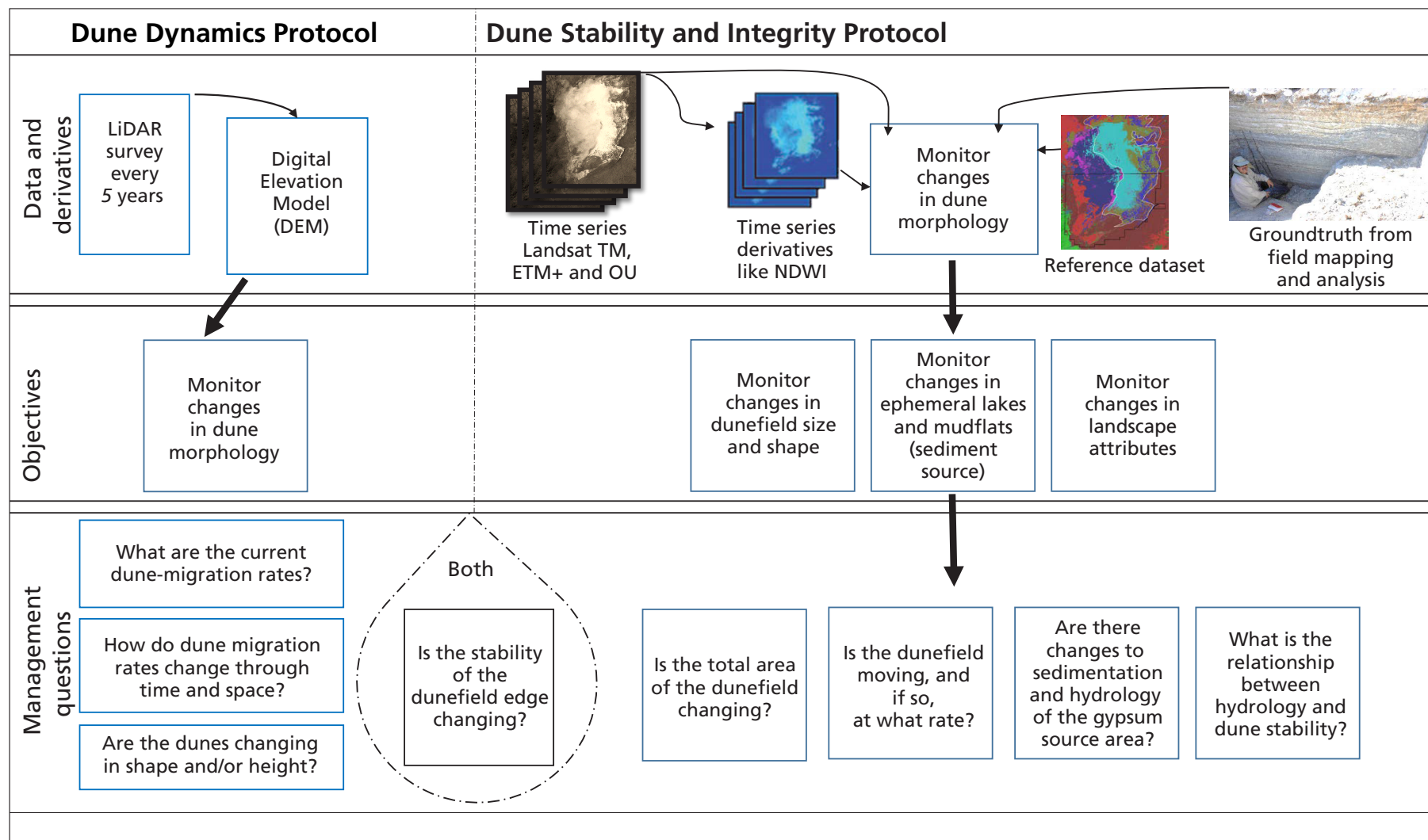


Figure 11. Research design schematic showing data and derivatives through the questions addressed by each protocol.

information on the expected future behavior of the system. These data, in the context of the reference set, will provide insight into the processes and products of the dynamic system and allow for establishing baselines for change of system attributes (e.g., dune edge movement or flooding).

Phase III will be an ongoing study of the system that will periodically add new data from remote sensing to the time series data. Every five years, this information will be incorporated into the analysis, punctuated by occasional inter-interval assessments if needed or desired. A full trend analysis with management recommendations will be completed every five years in tandem with LiDAR work (last flight: August 2015). This phase will be managed by CHDN, with park staff providing a supporting role.

4.3 Remote Sensing Overview

4.3.1 *Areal Extent of the Dunefield to be Monitored by Remote Sensing*

The monitoring area of interest is the entire White Sands dunefield, encompassing White Sands NM, Holloman AFB, and the White Sands MR. Landsat imagery from path 33, row 37 covers the full dunefield and surrounding area. Given that the entire dunefield encompasses 712 square kilometers, approximately 791,000 Landsat 30-meter pixels should be generated ($\sim 712/0.0009 = \sim 791,000$ pixels). This resolution is adequate to track long-term or cumulative changes through time. Where higher resolution (i.e., precision) may be required, such as for vegetation analyses, imagery from the NAIP is available on a 2–3 year cycle, providing 1-meter spatial resolution. Higher-resolution imagery is also available from commercial satellite systems.

4.3.2 *Image Sources and Specifications*

Imagery from the Landsat Thematic Mapper (Landsat 8) is easily obtained from the U.S. Geological Survey in a format that is readily usable in a variety of GIS and image-processing software. The imagery can be obtained in a pre-processed state that includes geometric registration. The multispectral channels of the system are provided as 30-meter spatial

resolution pixels, while the panchromatic band is 15 meters. Images are available on 16-day intervals, but not all images are usable if targets are obscured by clouds. Using the red-green-blue clustering of multi-temporal imagery, movement (direction and extent) can be documented.

The NAIP acquires aerial imagery during the agricultural growing seasons in the continental U.S. A primary goal of NAIP is to make digital orthophotography available to governmental agencies and the public within a year of acquisition. NAIP imagery is also freely available as geometrically corrected Digital Ortho Quarter Quads at 1-meter spatial resolution pixels or as Compressed County Mosaics, also at 1-meter resolution once annually (typically during the agricultural growing season). Due to its high spatial resolution, this imagery can be interpreted to identify the location and types of dunes within the dunefield, as well as individual shrubs and trees.

Imagery from commercial systems, such as DigitalGlobe's WorldView 2 and 3, can be downloaded via the Enhanced View Web Hosting Service site or through the Web-based Access and Retrieval Portal and its successor, and analyzed in the same way as the NAIP imagery. NAIP and WorldView imagery are, for analytical purposes addressed herein, comparable. Google Earth also provides substantial resolution to discern individual trees, if necessary.

There are multiple sources of processed MODIS data for calculating EVI and NDVI (from Thoma et al. 2017) (Table 4). These sources differ primarily in the number of days included in a single composite, in the type of smoothing, in the level of processing, and in the speed with which data are made available (Table 4). At time of this writing, the Northern and Southern Colorado Plateau Inventory and Monitoring networks were using MODIS data distributed by the EROS Land Processes Distributed Active Archive Center (DAAC) and by the National Snow and Ice Data Center DAAC. However, other MODIS data sources may be used in the future, depending on network needs and availability of different MODIS products.

Table 4. Examples of MODIS data sources and characteristics.

MODIS data source	Smoothed	Phenology metrics calculated	Composite days/ Bands per year	Availability
LP DAAC	NO	NO	16 / 23	Within a week
EMODIS	NO	NO	7 or 10 / variable	Within a week
MODIS4NACP	YES	YES	8 / 46	Episodic, unscheduled
LANCE-MODIS	NO	NO	Daily	Within hours

4.4 Analytical Approach: Change Detection

Change detection for the Landsat, NAIP, or other high-resolution imagery is a simple comparison of two dates of imagery and can be completed using GIS, such as ArcMap; or an image-processing system, such as ERDAS IMAGINE or ENVI. Dates need to be selected as a baseline for comparison; subsequent dates of imagery will be compared to the baseline to document any noticeable change in areal extent or movement of the dunefield or changes in vegetation coverage. Selecting winter dates will provide a lower sun angle, which will help enhance the dunes through higher contrast between sunlit and shaded sides. At the time of analysis, pre-processing and QA/QC (quality assurance/quality control) directly relevant to the particular image types need to be followed to ensure analysis integrity.

4.4.1 Image Pre-processing: Radiometric Normalization

Spectral data acquired by satellite sensors are influenced by a number of factors, such as atmospheric absorption and scattering, sensor-target-illumination geometry, sensor calibration, and image data-processing procedures, which tend to change through time (Teillet 1986). Targets in multi-date scenes are extremely variable and have been nearly impossible to compare in an automated mode (Kim and Elman 1990). To detect genuine landscape changes as revealed by changes in surface reflectance from multi-date satellite images, it is necessary to carry out radiometric correction. Two approaches to radiometric correction are possible: absolute and relative (Lo and Yang 1998). The absolute approach requires the use of ground measurements at the time of data acquisition for atmospheric correction and sensor calibration.

This is not only costly but also impractical when archival satellite image data are used for change analysis (Hall et al. 1991). The relative approach to radiometric correction, known as relative radiometric normalization, is preferred because no in situ atmospheric data at the time of satellite overpasses are required. This method involves normalizing or rectifying the intensities or digital numbers of multi-date images, band-by-band, to a reference image selected by the analyst. The normalized images would appear as if they were acquired with the same sensor under similar atmospheric and illumination conditions to those of the reference image.

4.4.2 Image Registration

Good image registration is essential for change detection. Acceptable root mean square errors should be maintained below one pixel based on not less than 25 image registration points in the image. Thus, the dunefield area can be effectively delineated with image-difference techniques after careful registration and radiometric normalization because the perimeter-to-area ratio is small. For this reason, image-registration error is a negligible component of estimated change in area.

4.4.3 Using Remote Sensing to Detect Changes in the Dunefield

Landsat, NAIP, or other imagery can be used to evaluate gross changes in the White Sands dunefield over time. Comparisons of images that cover the entire White Sands dunefield will be made every five years. Figures 12–14 show a series of Landsat and NAIP images of the entire dunefield and the east margin of the dunefield with varying levels of resolution for two time periods, along with a subsequent difference image that shows the

changes that occurred (see SOP #3). Based on these difference images, it appears that the east margin of the dunefield was quite stable during this period. Similar imagery for other parts of the dunefield can be used to illustrate the same point and, moreover, provide a useful method for ascertaining changes.

Detecting and monitoring vegetation cover will require the higher spatial resolution of NAIP imagery or commercial satellite imagery. Imagery will need to be acquired during the time of maximum greenness in order to provide the highest contrast with the background and allow for NDVI calculations.

The resulting product will indicate areas of vegetation from different dates, areas where vegetation was lost, and areas where new vegetation has been established, and allow calculation of the difference in areas through time.

Image difference as proposed using Landsat will suffice for MODIS. The higher radiometric resolution of the MODIS sensor will allow better discrimination of gross vegetation change. EVI is the preferred method for change detection in minimally vegetated areas.

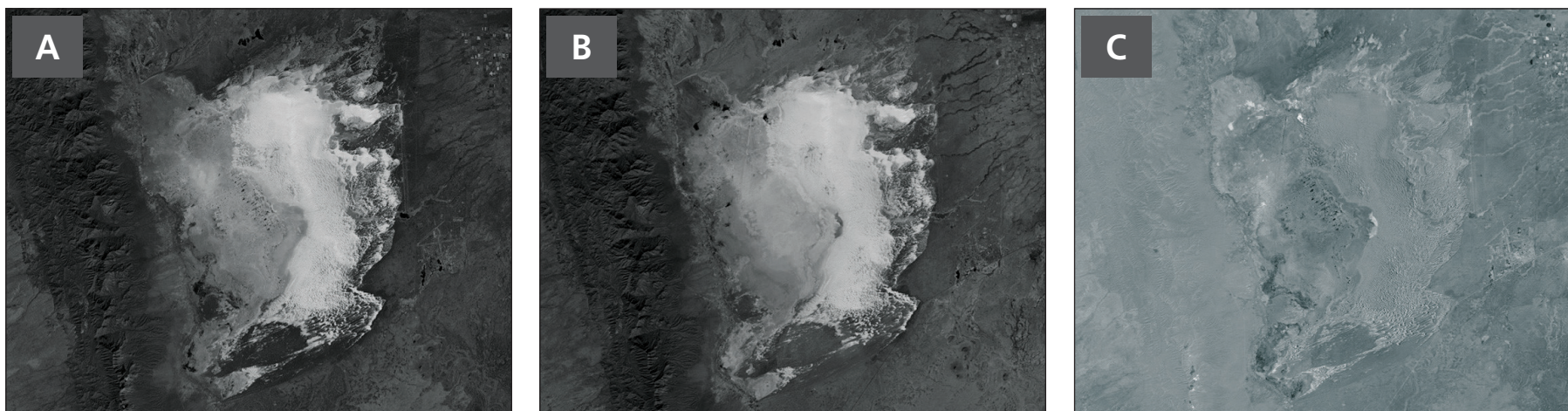


Figure 12. 30-meter resolution comparison from Landsat images and the resulting difference image for the entire White Sands dunefield (including Holloman AFB and White Sands MR), 1984 (A) and 2015 (B). The white areas in the difference image (C) show the changes occurring in the dunefield in the intervening period, which are negligible at this resolution. Prevailing winds are from southwest to northeast. Source: (A) Landsat 5 TM Image, (B) Landsat 8 Image, (C) Landsat Images 1984–2015.

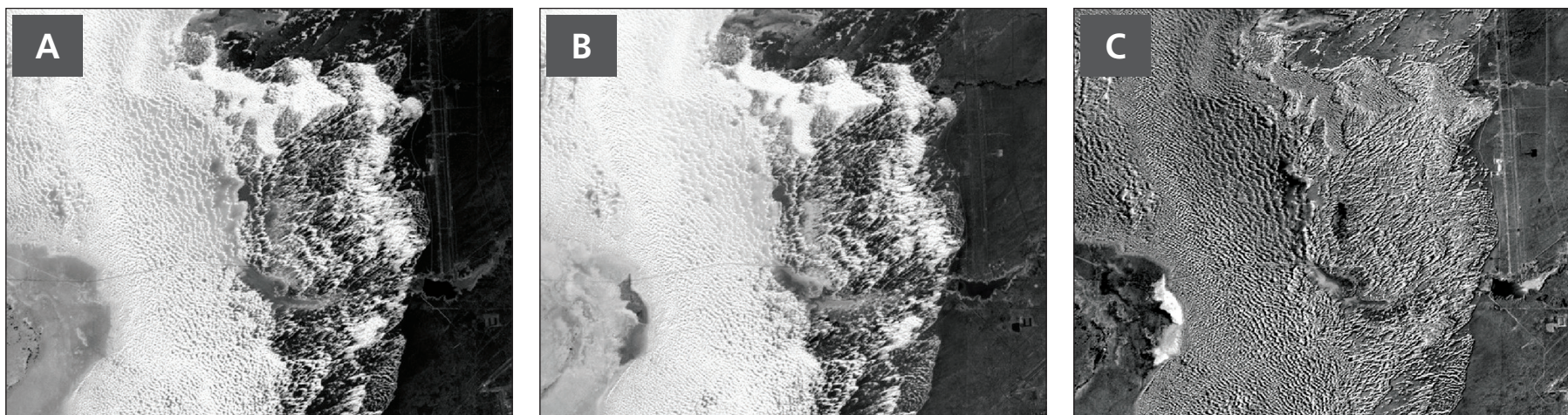


Figure 13. 30-meter resolution comparison from Landsat images and the resulting difference image of the east margin of the dunefield (including Holloman AFB and White Sands MR), 1984 (A) and 2015 (B). The white areas in the difference image (C) show the changes occurring in the dunefield in the intervening period. Note differences in interdunal movement, whereas the margin shows minimal changes at this resolution. Prevailing winds are from southwest to northeast. Source: (A) Landsat 5 TM Image, (B) Landsat 8 Image, (C) Landsat Images 1984–2015.

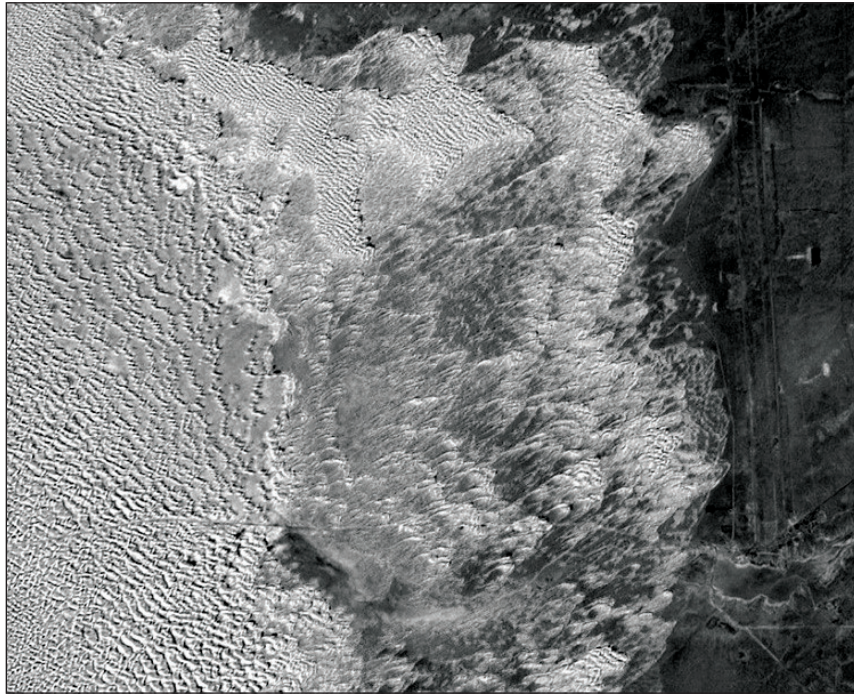


Figure 14. 15-meter Landsat difference image (15-m resolution panchromatic bands) for the same east margin of the dunefield (including Holloman AFB), 2000–2015. The white areas of this image show the changes occurring in the dunefield in the intervening period, 2000–2015. Note differences between this image and the 30-meter resolution difference images (Figures 12C and 13C). Prevailing winds are from southwest to northeast. Graphic created from LandSat7 (11/1/2000) and LandSat8 (11/3/2015) imagery.

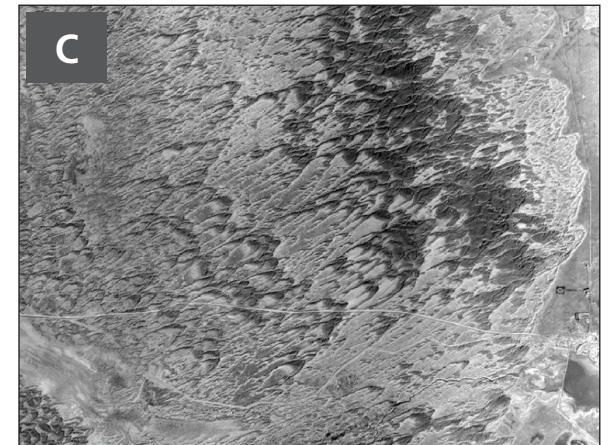
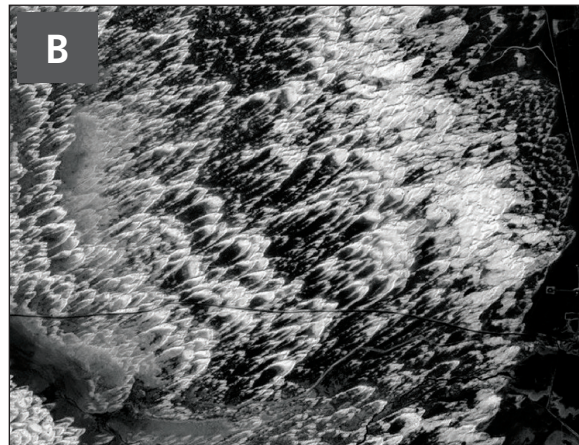
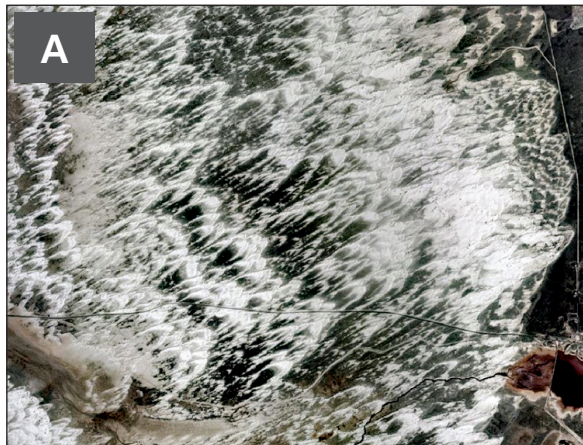


Figure 15. 1-meter resolution comparison from NAIP and WorldView images and the resulting difference image of the east margin of the dunefield (including Holloman AFB), 2009 (A) and 2015 (B). The white areas of the difference image (C) show the changes occurring in the dunefield in the intervening period. Note slight differences are detectable at 1-m resolution in NAIP images relative to Landsat. While noteworthy, these changes may not be geomorphologically significant, given that they are minor and undetectable at coarser scales. Direction of change is unknown (increase or decrease). Prevailing winds are from southwest to northeast. Source: (A) NAIP Image 2009_1 meter resolution, (B) Worldview Image 2015_1 meter resolution, (C) NAIP 2009-Worldview Image 2015_1 meter resolution.

5 Data Management Procedures

Analyses using the Landsat will occur every five years, concurrent with contracted LiDAR work.

NPS will archive the raw data (including raw and classified LAS [LiDAR] files) and all reports to ensure the data can be used and maintained into the future. Data analysis will be performed either by an Inventory & Monitoring (I&M) GIS technician within the Southwest Network Collaboration (CHDN/Sonoran Desert Network/Southern Plains Network), by the Intermountain Region (IMR) GIS specialist, or through contracting. Specifications for analyses will be included in the contract, if used. NPS will archive the raw and classified LAS files and all reports from the vendor.

Data will be archived onto a local CHDN network server that is backed up or can be sent to the national I&M office in Fort Collins, Colorado. Project files will be formally archived at the Western Archeological and Conservation Center in Tucson, Arizona.

Bare earth or surface digital elevation models (DEM) (ASCII and ESRI GRID format) will be broken up into reasonable tiles based on area of coverage and a mosaic of all tiles, and a set of data reports that include a flight report, ground control report, LiDAR system data report, a system calibration report and data processing procedures for files posted. All ground-control data will be provided to the NPS. The vendor will create metadata for the entire DEM datasets, not each individual tile. The analyses will be compliant with Federal Geographic Data Committee standards and document all data collection and processing procedures, as well as the horizontal and vertical datum and projections.

6 Reporting and Analysis

6.1 Data Analysis and Reporting

Data analysis and status and trend reporting will occur every five years, concurrent with the LiDAR monitoring for the dune dynamics protocol (Smith et al. 2016). Status and trend reports will be published in the NPS Natural Resource Reports (NRR) publication series after enough data cycles have been analyzed to generate trends.

6.1.1 Status Reports

The reports will be prepared by CHDN staff with support from the GIS specialist conducting the analyses. Status reports are intended to (1) describe the current condition (status) of dunefield stability (area, centroid, and dunefield margins), (2) interpret these conditions in the context of historical and other analyses on other historical changes occurring in other dunefields, and (3) explain the sampling and analysis techniques, effort, and level of certainty upon which the data and interpretations are based.

Draft status reports will be reviewed by park staff or other designated representatives for sensitive data and policy implications as per NPS Director's Order #66. During this review, draft reports will be available to NPS employees only via the CHDN Sharepoint site. If reports are deemed to include restricted data, they will be made available only through internal servers. Redacted versions may be distributed to the public. Based on our past experience, very few reports will be determined to contain restricted data.

Pending successful peer review, final status reports will be submitted for publication in the NPS NRR series and posted on the network's website.

6.1.2 Trend Reports

The network will produce a trend report after every third data-collection cycle (year 15) and/or using the historical data analyses, and then every five years thereafter. These synthesis reports are intended to (1) describe trends (if any) in the stability and integrity

of the dunefield using appropriate time series analytical techniques, (2) use modeling and other data-exploration techniques to evaluate potential explanatory variables and covariates over broad thematic and spatial scales, and (3) synthesize this wide-ranging information to explore patterns and better understand processes of dune dynamics. Status information for the third monitoring cycle will also be presented in the trend report. The CHDN program manager will direct the production of this report with support from the cooperator of record during the third monitoring cycle. Other network staff and external subject-matter experts may also be involved.

Draft trend reports will be reviewed by the park staff. In addition, these reports will undergo an external science review, to be coordinated by CHDN and IMR regional program managers. The purposes of this review are to (1) ensure that the report and its conclusions are founded on sound science and (2) encourage additional input on candidate explanations and approaches for additional synthesis and suggest high-priority research.

Upon successful completion of all reviews, final trend reports will be submitted for publication in the NRR series and/or peer-reviewed scientific publications. These reports will be distributed to park staff, cooperators, and the interested public. The report and derived communication products will be served on the network's website and on the Science of the American Southwest website. Designed to reach a varied audience (agency managers and resource specialists, university scientists and students, educators and guides, members of the public and press, and other stakeholders), this website presents data in a hierarchy of increasing detail, allowing users to access both general concepts and project-specific results.

6.2 Process Notifications

The network program manager or designee will notify the park's superintendent, CHDN board of directors, technical committee, and/or other designated representatives after

completion of each of the major steps in the analysis of remote-sensed images. The purpose of these notifications is to ensure that the park or other designated representatives

are aware of progress in the monitoring cycle, and to alert the designated representative of any problems.

7 Personnel Requirements and Training

Individuals who will work with Landsat, NAIP, MODIS, or other images need to be trained in the use of GIS software and

the analysis techniques required for these analyses.

8 Operational Requirements

The necessary NPS equipment includes a computer and GIS software. The computer should have at least 16GB of RAM and a high-end graphics processor card with at

least 2GB of RAM. It is also recommended that a large monitor (30 inches) be used when analyzing and studying the DEMs.

9 Revising the Protocol

In general, once published, the protocol narrative will be revised only if major changes are made to the protocol proper. “Major” pertains to significant departures that change the scope or objectives of the protocol. In contrast, the SOPs are specific, step-by-step instructions for performing tasks that ultimately result in analysis and publication of the results of the monitoring and the quality-checked data sets. SOPs are expected to be revised more frequently than the protocol narrative.

Careful documentation of each revision (narrative or SOP) must include an archive of previous versions. This is essential for maintaining consistency in data collection, analyses, and reporting. To summarize changes, the monitoring database for each component contains a field to identify the protocol version used to gather and analyze data.

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